DEVELOPMENT OF AN IMPROVED METHODOLOGY FOR ANALYZING EXISTING SINGLE-FAMILY RESIDENTIAL ENERGY USE

A Dissertation

by

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ABSTRACT

The purpose of this study was to develop an improved methodology for analyzing the energy use from existing single-family. The overall goal of this work is to make home energy audits more effective by providing homeowners and energy auditors with an improved and reliable tool to identify over-consumption in a residence by showing where the energy is inefficiently being used in the residence when compared to buildings of similar size in similar climates. Such a tool can be used by auditors to quickly assess the problems in the building, determine accurately what needs to be fixed and to provide useful guidance before arriving on-site. In order to accomplish this, an improved methodology for an easy-to-use, semi-automatic calibrated simulation that can determine potential energy conservation measures for single-family residences was developed and tested.

As a first step, an easy-to-use simulation which can be used by homeowners who are not familiar with residential building energy analysis was developed. Users of this easy-to-use simulation are only required to input basic information of their houses such as construction year, size and location of the house, with the other inputs for building energy simulation being filled-in automatically using a newly established statistical house information database for Texas. Next, the easy-to-use simulation is calibrated using the semi-automatic calibrated simulation methodology that matches the simulated and actual utility electricity and natural gas use of the house. In order to develop this methodology, a sensitivity analysis was performed using a three-parameter change-point

regression model that regresses the energy use against ambient temperature. The analysis showed the most significant simulation parameters that affect residential energy use that are decomposed into the baseload, the change-point temperature, and the cooling or heating slope. These parameters were used to calibrate each part of the building energy use against the actual monthly electricity and natural gas use.

In the next step, the calibrated simulation parameters were compared with similar input parameters of a standard house that is compliant with the 2009 IECC to determine the differences in the parameters and give guidance about what characteristics of the house were below the energy efficient characteristics of the 2009 IECC-compliant house. Using this comparison, the less energy-efficient parameters of the house were determined as potential energy conservation measures for a future retrofit, and finally, the most cost effective measures were determined through a simple pay-back cost analysis.

In order to verify the methodology, the both methods were tested on actual residence and the results were compared to determine if both procedures identified the same potential energy conservation measures. Once the procedure was demonstrated on the first case-study house, two additional houses were also tested to verify how well the procedure worked. The comparisons showed that the easy-to-use and the actual simulations resulted in the same potential energy conservation measures with the similar pay-back period, and thus was verified that the easy-to-use simulation can be used for a home energy audit procedure with reliability.

DEDICATION

To my parents

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CHAPTER I

INTRODUCTION

1.1 Background

Increasing demand and higher prices for electricity have steadily occurred since the energy crisis of 1973. Since the energy crisis, the United States government has established a number of policies to reduce energy demand by improving of the efficiency of buildings, including the Energy Policy and Conservation Act (EPCA) of 1975, the National Energy Conservation and Policy Act (NECPA) of 1978, the National Appliance Energy Conservation Act (NAECA) of 1987, the Energy Policy Act (EPACT) of 1992 and 2005, and the Energy Independence and Security Act (EISA) of 2007[1]. As a result, energy efficiency, especially in the building sector, has become a major issue in the United States (Benningfield et al. 2003).

In addition to the United States government, energy related technical societies, such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the International Code Council (ICC), have also made efforts to improve building energy efficiency in new buildings by publishing energy efficiency standards. In response to the 1973 oil embargo, ASHRAE first published ASHRAE Standard 90 for new buildings in 1975. In 1989 the standard was divided into residential (90.2) and commercial (90.1) codes (Hydeman 2006). During this same period, the first Model Energy Code (MEC) was published in 1983 by the Council of American Building

[1] Descriptions of these policies are shown in Table C.1 in the Appendix C.

Officials (CABO), and was then revised and renamed as the International Energy Conservation Code (IECC) in 1998 by the ICC. The revisions to the standards are shown in Figure C.1 and Figure C.2 in the Appendix C. Currently, most states in the United States use either the IECC or ASHRAE Standards as their minimum building energy codes (U.S. DOE 2008a). As a result of the efforts of the United States government and other relevant societies, significant improvements in new building energy efficiency have been made (Krarti 2010). Although the energy efficiency of new buildings has improved by adopting and following the ASHRAE and IECC standards, the vast majority of existing buildings are more than 20 years old, and need to be retrofitted for improving energy efficiency (Krarti 2010).

In a similar fashion to new buildings, technical societies such as ASHRAE have also published standards and guidelines to improve energy efficiency of existing buildings. ASHRAE Standard 100-2006 (ASHRAE 2006), Standard 105-2007 (ASHRAE 2007a), Guideline 0-2005 (ASHRAE 2005a), and Guideline 1.1-2007 (ASHRAE 2007b) are good examples of the standards and guidelines that apply to existing buildings. Additionally, other societies have also made similar efforts to improve energy efficiency. For example, the United States Green Building Council (USGBC) established the Leadership in Energy and Environmental Design (LEED) rating system not only for new buildings, but also for existing commercial buildings, called the LEED-EB for Existing Buildings (USGBC 2008). Similarly in 2006, the Residential Energy Services Network (RESNET) was created to provide a method to assess home energy efficiency based on standards and their potential for improvement of existing homes and new construction, called the Home Energy Rating System (HERS) (RESNET 2006). Descriptions of these standards, guidelines, and programs are shown in Table C.2 in the Appendix C. From these efforts, many opportunities to be more energy efficient in existing buildings have become more evident (Holness 2008).

However, despite the efforts of the United States government and other relevant societies who published standards, guidelines and programs, the actual improvements in energy efficiency to existing buildings is often influenced more by who works on the retrofits than by the retrofit itself. In addition, the on-site data gathering procedures for an energy audit of a building are a time-consuming process because it includes the collection of a large range of information to be gathered on-site during a walk-through examination, including: information about the building envelope and HVAC systems; followed by an analysis of the building energy use by building energy simulation; and then an evaluation of the energy conservation measures for the buildings. Therefore, there is a need to develop a consistent, well-documented and easy-to-use procedure that requires little or no expertise in simulation and HVAC systems, yet provides an accurate and cost-effective energy efficiency analysis of an existing building.

1.2 Purpose and Objectives

The purpose of this study is to make the home energy audits more effective by providing the auditor with an improved and reliable tool to show where the energy is inefficiently being used in a residential building when compared to buildings of similar size and age in similar climates. Such a tool can be used by auditors to quickly assess the problems in the building, determine what needs to be fixed more accurately and quickly before arriving on-site.

The objective of this study is therefore to develop and test an easy-to-use, semi-automated methodology for analyzing single-family, detached residential energy use. The semi-automated-audit methodology will utilize a minimum number of inputs for the simulation by using previously gathered information from publically-available sources, along with specially developed indices.

Tasks to accomplish the objectives are:

1) Conducting a literature review regarding building energy codes, home energy audits, measurement and verification methods for measuring home energy savings, and energy estimating and modeling methods for residences;
2) Developing a semi-automated home energy audits methodology;
3) Selecting and characterizing a case-study single-family house, and applying the developed methodology to the house;
4) Simulating the case-study house using the newly developed calibrated methodology;
5) Testing the procedure with additional single-family houses; and
6) Developing a generalized procedure of analyzing single-family house energy use using a semi-automated-methodology.

1.3 Organization of the Dissertation

This dissertation is divided into six chapters, which include: 1) Introduction,

2) Literature Review, 3) Significance and Limitations of the Study, 4) Methodology, 5) Results, and 6) Summary and Future Work.

Chapter I presents an introduction to this study by providing a background, the purpose and objectives of this study. Chapter II reviews the literature related to this study, which includes: building energy codes; home energy audits; measurement and verification methods of measuring energy savings; and different types of energy estimating and modeling methods in terms of *forward* and *data-driven methods*. Chapter III describes the significance and limitations of this study. Chapter IV describes the methodology for semi-automated home energy audits, which includes: 1) The development of the methodology for easy-to-use simulation, 2) The development of the methodology for semi-automatic calibrated simulation, 3) The development of the methodology for the determination of potential energy conservation measures in single-family houses, and discussed the procedures used in this study. Chapter V presents the analysis and results of the study. Finally, Chapter VI summarizes this study, and proposed recommendations for future research.

CHAPTER II

LITERATURE REVIEW

The literature reviewed for this dissertation is related to building energy codes, including code compliance software for residential buildings and the residential or Home Energy Rating System (HERS) in the United States; home energy audits, including energy conservation measures for the building envelope, electrical and lighting systems, HVAC systems; measurement and verification methods of measuring energy savings; and different types of energy estimating and modeling methods in terms of *forward* and *data-driven methods*.

The literature review includes journals (i.e., the ASHRAE Journal, the American Society for Mechanical Engineers (ASME) Journal of Solar Energy Engineering, the Energy Journal, Energy and Buildings Journal and the ASHRAE HVAC&R Research Journal), conference proceedings (i.e., the American Council for an Energy-Efficient Economy (ACEEE) Summer Study on Energy Efficiency in Buildings, the ASHRAE Transactions, the ASME International Solar Engineering Conference, the ASME-Solar Energy Division (SED) International Solar Energy Conference, the International Building Performance Simulation Association (IBPSA), the International Conference for Enhanced Building Operations (ICEBO) and the Symposium on Improving Building Systems in Hot and Humid Climates), related publications by ASHRAE (ASHRAE Guideline 14-2002 , the 2009 ASHRAE Handbook of Fundamentals, ASHRAE Research Projects and ASHRAE Standard 140-2011), publications by selected laboratories (the Energy Systems Laboratory (ESL), the National Renewable Energy Laboratory (NREL), the Lawrence Berkeley National Laboratory (LBNL), the Oak Ridge National Laboratory (ORNL) and the Pacific Northwest National Laboratory (PNNL)), publications by selected organizations (the California Energy Commission and the Residential Energy Services Network (RESNET)), publications by selected universities (Princeton University, Texas A&M University, the University of Colorado and the University of Dayton), publications by the United States Department of Energy (U.S.DOE) (the Energy Information Administration (EIA), the International Performance Measurement and Verification Protocol (IPMVP), the Measurement and Verification Guidelines and the North American Energy Measurement and Verification Protocol (NEMVP)) and related books. The findings from the literature review are discussed in the following section.

2.1 Building Energy Codes

2.1.1 History of Building Energy Codes

Beginning in the 1960s a series of energy crises resulted in the development of more energy efficient building codes in the United States. The first crisis was the electricity blackout in November of 1965. This was caused by electricity overloads from a transmission line out of commission, and occurred mostly on the East Coast of the United States, which includes New York City (Standler 2011). As a result of this crisis, energy efficiency standards began to be developed for non-residential buildings including high-rise residential buildings. The development of the energy efficiency standards accelerated throughout the United States after the energy crisis of 1973. One of the most important efforts was ASHRAE's new energy efficiency standard for new buildings in 1975; ASHRAE Standard 90 (NCSBCS 2001). In 1989, the standard was divided into two standards, one for residential and one for commercial (Hydeman 2006). At this same time in 1977, the U.S. DOE was established, as a result of the combination of the Federal Energy Administration and the Federal Power Commission, and related programs from various other agencies. Shortly after this, in 1983, the first Model Energy Code (MEC) was published by the Council of American Building Officials (CABO). Nine years later in 1992, the United States adopted the Energy Policy Act (EPACT 1992); this legislation established the MEC as the basis for the energy code for residential buildings, with ASHRAE Standard 90.1 as the basis for the energy code for non-residential and high-rise residential buildings in the United States. However, at this time, adopting these energy codes was not a requirement for all states. In 1998, the International Code Council (ICC) was formed in the United States to serve as one organization for building code organizations, and the MEC was renamed as the International Energy Conservation Code (IECC).

Since that time, many states have adopted the IECC for residential buildings (Benningfield et al. 2003). In addition, some states have developed their own building energy efficiency standards; for example, the State of California is currently using their own developed energy efficiency standard called the 2013 Building Energy Efficiency Standards (CEC 2013), which is more stringent than the 2009 IECC for residential and ASHRAE 90.1-2007 for commercial buildings. The State of Florida is also currently using their own developed standard called the 2010 Florida Building Code (ICC 2011), which is more stringent than 2006 IECC for residential and ASHRAE 90.1-2007 for commercial buildings. In the State of Texas, the Texas Building Energy Performance Standards (TBEPS) were established in 2001 and are currently being used. The TBEPS currently uses the 2009 IECC and 2009 IRC (International Residential Code) for residential, and the 2009 IECC for commercial buildings (SECO 2012).

2.1.2 Energy Code Compliance Software for Residential Buildings

The U.S. DOE has run the Building Technologies Program (BTP) as a nationwide plan. The BTP has been divided into several programs such as the Better Buildings program, the Building America program, and the Building Energy Codes program. The Building Energy Codes program coordinates with government agencies, states and local jurisdictions, and other organizations to promote stronger building energy codes, and helps to improve building energy efficiency through activities in three major areas: Model Code Development, Code Compliance Software, and Code Education, Training, and Advocacy (U.S. DOE 2011a). The Building Energy Codes program distributes free code compliance software, which includes REScheck™ and COMcheck™ developed by the Pacific Northwest National Laboratory (PNNL) as a part of the Code Compliance Software. Furthermore, the PNNL works collaboratively with the ASHRAE, the ICC, and the states to improve energy efficiency in building energy codes (PNNL 2012). These free tools are designed to check compliance with the IECC, and the ANSI/ASHRAE/IESNA Standard 90.1 codes, which are the basis for most state codes (U.S. DOE 2011b).

However, before any software is used for code compliance, it first needs to be verified. The RESNET, which is a nonprofit organization created by the NREL and the Florida Solar Energy Center (FSEC), in cooperation with the U.S. DOE has created a code compliance software verification committee to serve as an advisory group to develop test suites for the software (RESNET 2007). The RESNET verification procedure is a set of tests that are required for verifying the accuracy and comparability of the IECC compliance-software. The RESNET software verification procedure consists of the five test suites: 1) Tier one of the HERS BESTEST (Judkoff and Neymark 1995a, 1995b); 2) IECC Code Reference Home auto-generation tests; 3) Heating, Ventilation, and Air Conditioning (HVAC) tests; 4) Duct distribution system efficiency tests; and 5) Hot water system performance tests (RESNET 2007).

Five programs were reviewed as examples of energy code compliance software: REScheck™, which offers either a prescriptive or a UA trade-off approaches to compliance, REM/Rate™, REM/Design™, EnergyGauge® USA and the International Code Compliance Calculator (IC3), which offer a simulated performance path approach. REScheck™ was chosen because the program was developed by the U.S. DOE Building Technologies Program, and REM/Rate™ and REM/Design™ were chosen because it is a RESNET-accredited software for use nationwide. Additionally, EnergyGauge® USA and IC3 were chosen because they are also RESNET-accredited software and primarily used in hot and humid climates. Short descriptions of each of the software programs are included in the following subsections.

2.1.2.1 REScheck™

In1997, the U.S. DOE tasked the PNNL with developing the MECcheck™ code compliance software for single-family and low-rise multi-family residential buildings. Later in 2002, MECcheck™ was renamed REScheck™ (Bartlett et al. 2011). REScheck™ is the most widely used code compliance software in the United States even though it is not a RESNET-accredited. REScheck™ is an UA trade-off approached code compliance software that uses DOE-2.1e as the simulation program for showing compliance with the variety of energy codes, which is only focused on the thermal envelope (Seiter 2007; EnergyLogic 2012). REScheck™ demonstrates compliance with 1992, 1993, and 1995 editions of the MEC, the 1998, 2000, 2003, and 2006 editions of the IECC; the 2006 IRC, and the following state and county residential codes: Arkansas, Georgia, Minnesota, New Hampshire, New York, Vermont, Wisconsin, and Pima County, Arizona (PNNL 2008). REScheck™ is available in a web-based version and downloadable desktop version for use on Windows and Mac operating system. A useful feature of the REScheck™ is the Beyond Code Advisor in the desktop version. This feature links to a detailed resources, such as ENERGY STAR and Building America, which expand the details of specific energy components (Seiter 2007).

2.1.2.2 REM/Rate™ and REM/Design™

REM/Rate™ and REM/Design™ are code compliance software for Windows operating system for new and existing single- and multi-family residential buildings. REM/Rate™ and REM/Design™ were developed and maintained by the Architectural Energy Corporation (AEC) since 1985 and are RESNET-accredited software and based on the SUNREL program, which was upgraded version of the SERI-RES (AEC 2004), for calculating annual energy use. Both REM/Rate™ and REM/Design™ provide compliance with the various energy codes, including 1992, 1993 editions of the MEC, and 1998, 2000, 2001, 2003, 2004 and 2006 editions of the IECC. The REM/Rate™ and REM/Design™ are nearly identical with the major difference being that REM/Rate™ provides three more optional functions, including HERS, EnergyStar and 2005 EPACT Tax Credit certifications (AEC 2008; U.S. DOE 2012b).

2.1.2.3 EnergyGauge® USA

In 1996, the Florida Solar Energy Center (FSEC) started to develop the EnergyGauge® USA code compliance software that performed calculations and ratings of the energy use of new and existing residential buildings. EnergyGauge® USA is a DOE-2.1e simulation program, which is accredited by the RESNET. It allows users to examine many different energy saving and renewable energy options based on hourly calculations (Fairey et al. 2002). There are three versions of EnergyGauge® USA, including a Florida residential version, called FlaRes 2010, a nationwide residential version for building code compliance, called ResSim, and a nationwide residential version of building code compliance and HERS ratings, called ResRate (Mann 2009). The FlaRes 2010 demonstrates compliance with the 2010 Florida Building Code. Whereas, ResSim and ResRate are code compliant software for use with the IECC 1998/2000, IECC 2002, 2003, 2004 and 2006 (FSEC 2012).

2.1.2.4 International Code Compliance Calculator (IC3)

The International Code Compliance Calculator (IC3) is another residential code compliance and above-code compliance software developed in 2007 by the Energy Systems Laboratory (ESL) at the Texas A&M University. The IC3 is one of several web-based calculators, which were started in 2003 (Gilman et al. 2008). The IC3 is a RESNET-accredited, easy-to-use, web-based, code compliance software that calculates the energy savings using DOE-2.1e simulation program and calculates emission reductions using the United States Environmental Protection Agency's (USEPA) Emissions and Generation Resource Integrated Database (eGRID) for proposed single-family and multi-family houses in Texas. IC3 was created to provide technical support for the Texas Building Energy Performance Standards (TBEPS) for builders, home energy raters and code officials. The IC3 has a special version that has been used internally at the ESL, called DOE-2 Desktop Processor (DDP). In difference to the IC3, the DDP can submit multiple simulation runs using an input spreadsheet that gives instructions for the simulation of multiple runs, whereas the IC3 only allows one simulation run at a time (Liu 2008). Both the IC3 and the DDP share the same code compliant software program (Haberl et al. 2009).

2.1.3 Home Energy Rating System (HERS)

The Home Energy Rating System (HERS) developed by the RESNET provides a method to assess home energy efficiency for new and existing homes and has the potential for recommending improvements. HERS software is used to determine the most cost-effective building envelope and mechanical system retrofits to help a homebuyer compare the energy costs for different homes (Gardner 2008). HERS ratings provide an energy use index, called the HERS index, which is scored from 0 to 100; where an index of 0 indicates a zero energy building (i.e., a building that consumes no annual energy), while an index of 100 indicates a building that meets the 2006 IECC. Additionally, each one percent increase in the energy efficiency of a building corresponds to a one point decrease in HERS index number (i.e., a home with the HERS index of 60 is 40 percent more energy efficient than the home with a HERS index of 100) (Shultz 2008). Some states in the United States have developed their own HERS. For example, in the State of Florida, the FSEC has developed the EnergyGauge Program, formerly called the Florida Building Energy-Efficiency Rating System (BEERS). In the State of California, the California Energy Commission has developed the California Home Energy Rating System (California HERS) program (CEC 2008); and in the State of Texas, the Texas Home Energy Rating Organization (TXHERO) has developed the Texas Home Energy Audit Program (TXHERO 2011).

2.2 Home Energy Audits

2.2.1 History of Home Energy Audits

Home energy audits began to appear shortly after the oil embargo in 1973. The original home energy audit was typically in the form of a checklist or some other type of chart that an energy auditor could use to perform a walk-through examination of a residence. Using the checklist the auditor noted the problems in the building such as inadequate insulation of the building envelope or inefficient equipment on the checklist or a chart, wrote a report about the findings, based on the checklist and delivered the report to the homeowner. However, because the process relied heavily on the knowledge and experience of the auditors, several efforts have been made to standardize the auditing procedure. For example, ASHRAE has developed a uniform energy audit form, audit procedures, and recommendations for commercial buildings (Hay 1997). Additionally, RESNET has also published national standard for home energy audits for residential buildings (RESNET 2006). Finally, several energy auditing tools for residential buildings have been developed as well such as: the Home Energy Saver™ (U.S. DOE 2012a), EnergyInsights™ (Apogee 2012), and the National Energy Audit Tool (NEAT) (Gettings 2001) (SENTECH, Inc. 2010).

2.2.2 Home Energy Audit Procedure

Home energy audits are usually the first step of a residential energy conservation program. The home energy audit examines past energy use, evaluates future energy conservation measures (ECMs), and determines the potential energy savings in a building if the future ECMs were to be applied to the house (Zhu 2005). Generally, the home energy audit procedure starts by collecting information about the building envelope, HVAC systems and utility bills to help assess existing condition. These data are then analyzed to examine how energy is used, and what needs to be changed to reduce future energy use in the building. After that, selected changes are evaluated by estimating the energy savings and cost-effectiveness of each measure. This same process can be applied to other building types (i.e., commercial) even though the building details are different.

For single-family residential buildings, the energy audit may also examine past utility bills and combine the information with on-site visits to the building. During the visit, the auditor examines the building, including: the insulation levels of the thermal envelope such as the walls, roof, floor, windows, and doors, and also inspects the systems in the house such as the air-conditioner, heating system, and water heater, including information about the age, size, efficiency and past maintenance records of the systems. The ECMs for the building are then evaluated and recommendations are made, such as adding insulation to the ceiling, and/or replacing heating or cooling systems with a higher efficiency system (Doty and Turner 2009).

2.2.3 Energy Conservation Measures (ECMs)

Energy conservation measures (ECMs) can be considered in three categories for residential buildings, including, the building envelope, electrical systems and HVAC systems.

Obtaining information about the building envelope (i.e., walls, roof, floor, windows and doors) is important for an energy audit of a residential building because the energy use of residential buildings is strongly influenced by outside weather conditions due to heat gain or heat loss through walls and windows, and air infiltration through the building surfaces. Therefore, energy auditors should obtain information about the construction materials, such as the level of insulation in the walls, floor, and roof, the area of the house, as well as other building envelope assemblies, such as the type and the number of panes of glass for the windows, and whether or not the windows have a low-E coating. In addition, any repairs and replacements of any of these components should be noted along with any corresponding energy use changes (Krarti 2010). Commonly used ECMs for improving the building envelope include: adding thermal insulation to the wall and roof, replacing windows with more efficient windows, and reducing unwanted air leakage. For electrical systems, improved lighting and equipment can be considered as an ECM for improving energy efficiency. According to Foster (2008), residential lighting accounts for about 15% of the total residential energy use, and is widely acknowledged as a one of the important and achievable ECMs for a residence. For HVAC systems, the energy auditors should obtain the HVAC nameplate information to determine the type of the systems, operating schedule and maintenance records (Krarti 2010). For many systems, condition of the system can be determined by a visual inspection. On-site performance measurements are rarely performed in residential audits, although the benefits from measurements are previously shown to be effective.

2.3 Measurement and Verification Methods of Measuring Residential Energy Savings

Measurement and verification (M&V) is the process for quantifying retrofit energy savings delivered by the ECMs. In principle, the measurement of the retrofit energy savings can be obtained from comparing the energy use during pre- and post-retrofit periods. However, the changes in energy use between the pre- and post-retrofit periods are not only due to the retrofit itself, but can also be to other factors such as changes in weather conditions, levels of occupancy and HVAC operating procedures. Therefore, it is important to account for all these changes to determine the retrofit energy savings accurately (Krarti 2010). Several efforts have been made to overcome some of these problems, including the PRInceton Scorekeeping Method (PRISM). PRISM is one of the most widely-used residential utility bill analysis methods that can be used to overcome selected problems. More details of the PRISM are described in section 2.5.2.1.1.

M&V protocols in the United States have been developed since in the mid-1990s (Haberl and Culp 2009). In 1996, the North American Measurement and Verification Protocol (NEMVP) was established as the first nationally recognized M&V protocol for commercial buildings (U.S.DOE 1996). The NEMVP was updated and renamed as the International Performance Measurement and Verification Protocols (IPMVP) in 1997 (U.S.DOE 1997). Since then the IPMVP has been expanded into two volumes in 2001: Volume I for energy and water savings (U.S.DOE 2001) and Volume II for indoor environmental quality (U.S.DOE 2002). Volume III of the IPMVP was published in 2003, and covers protocols for new construction or renewables (U.S.DOE 2003). Recently Volume I of the IPMVP was updated in 2007 (U.S.DOE 2007). In addition to the IPMVP, several other efforts have been underway to establish a standardized procedure for calculating energy retrofit savings, including ASHRAE Guideline 14-2002: Measurement of Energy and Demand Savings in 2002 (ASHRAE 2002; Haberl et al. 2005), which is being updated.

2.4 Energy Estimating and Modeling Methods in 2009 ASHRAE Handbook of Fundamentals

According to Chapter 19 in the 2009 ASHRAE Handbook of Fundamentals (ASHRAE 2009), there are two broad categories for energy estimating and modeling methods; one is a *forward method* that is a modeling method for building and HVAC system design and associated design optimization, the other is the *data-driven method* that is a modeling method for existing buildings for establishing baselines and calculating retrofit savings (Figure 2.1).

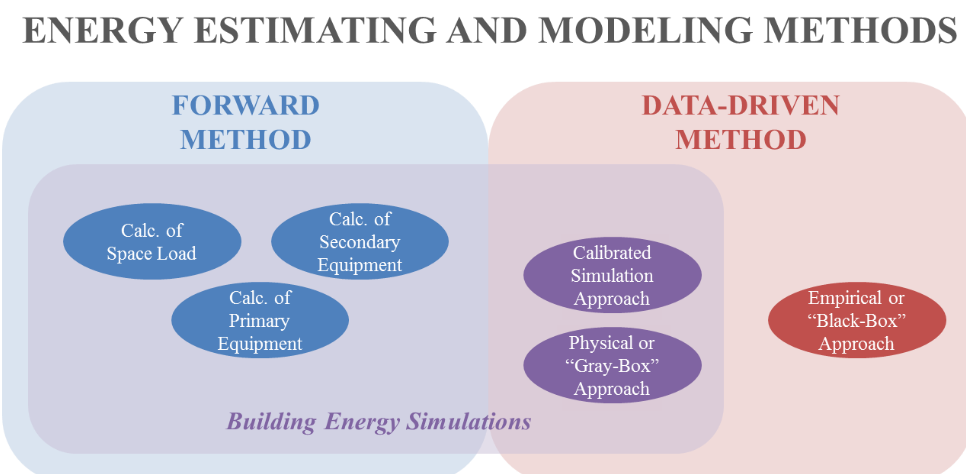

Figure 2.1 Diagram of Energy Estimating and Modeling Methods

2.4.1 Forward Method

According to the ASHRAE Handbook of Fundamentals (ASHRAE 2009), there are three steps in the *forward method*, including: calculation of space thermal load; modeling of the secondary equipment load (i.e., the equipment that distributes the heating, cooling, or ventilating medium to conditioned spaces); and modeling of the primary equipment (i.e., the central plant equipment that converts fuel or electricity to heating or cooling) energy requirements.

The first step in calculating energy requirements is to determine the space thermal load. The space thermal load must be determined in order to determine the amount of energy that needs to be added to or extracted from a space to maintain thermal comfort. Outdoor dry-bulb temperature, solar effects, internal gains, heat storage in the walls, roof and floors, and the effects of wind on both building envelope and infiltration should be considered in this calculation. The second step is translating the space thermal load into the secondary equipment heating and cooling load. Estimation of duct or piping losses or gains, electrical energy to operate fans and/or pumps should be considered in this calculation. Finally, the third step is calculating the fuel and/or energy required by the primary equipment to meet the loads of the secondary equipment and the peak electric demand on the utility system. Equipment efficiencies and part-load characteristics should be considered in this calculation.

2.4.2 Data-driven Method

The *data-driven method* first appeared in ASHRAE Handbook of Fundamentals in 1997 (ASHRAE 1997). At that time, the *data-driven method* was called the *inverse method*, which was renamed later as the *data-driven method* in 2001 (ASHRAE 2001b, 2005b, 2009). According to Chapter 19 in the 2009 ASHRAE Handbook of Fundamentals (ASHRAE 2009), the *data-driven method* for energy estimation in buildings and related HVAC systems can be classified into three categories, including:

1) an empirical or "Black-Box" approach, 2) a calibrated simulation approach, and 3) a physical or "Gray-Box" approach.

2.4.2.1 Empirical or "Black-Box" Approach

With the empirical or "Black-Box" approach, a single- or multi-variable regression model is used to predict the measured energy use based on various influential parameters (e.g., climatic variables, building occupancy, etc.). The regression models can be calculated using statistics or a combination of statistics and engineering formula to determine the energy use in the building. The model coefficients developed in an empirical model may or may not have physical meanings. This approach is usually appropriate for evaluating energy conservation measures in an actual building. Single-variable, multi-variable, change-point, Fourier series, and artificial neural network (ANN) models are examples of models included in this category.

2.4.2.2 Calibrated Simulation Approach

The calibrated simulation approach uses an existing building energy simulation program and tunes or calibrates the simulated energy use to closely match measured energy use by adjusting various input parameters of the program. The calibrated simulation can provide a more reliable energy analysis for an existing building, and it can be used as a retrofit building energy model to calculate savings. However, the accuracy of the calibrated simulation often varies from one simulation user to another because it relies heavily on the users' level of skill and knowledge in both the use of the simulation, practical knowledge about building operation, and ability to calibrate the simulation model.

2.4.2.3 Physical or "Gray-Box" Approach

The physical or "Gray-Box" approach first formulates a physical model of the building and HVAC system, which are based on engineering equations, then it identifies important parameters that represent aggregated physical parameters and characteristics, and determines the value of the parameters for a particular building using a statistical analysis.

2.5 Energy Estimating and Modeling Methods in the Related Literature

2.5.1 Forward Method

The *forward method* uses a known physical description of the building, HVAC systems and plant equipment such as building geometry, geographical location, physical characteristics (e.g., wall material and thickness), type of equipment and operating schedules, type of HVAC system, building operating schedules, plant equipment etc. to calculate peak and average energy use of the building using simulation (Haberl and Culp 2009). Building energy simulation programs such as DOE-2.1e, eQUEST and EnergyPlus are examples of programs that can be used in a *forward method*. The related literature was reviewed in this section corresponding building energy simulation programs.

2.5.1.1 Validation of Building Energy Simulations

The Building Energy Simulation Test (BESTEST) procedure was developed by NREL for systematically testing whole-building energy simulation models, and for diagnosing sources of predictive disagreement that may be caused by "… algorithmic differences, modeling limitations, coding errors, or input errors." (Judkoff and Neymark 2006). The BESTEST procedure is an effective way to quantitatively evaluate the appropriateness of building energy simulation models (Judkoff and Neymark 1998). The BESTEST procedure uses a "comparative testing" approach where a model is compared to itself or to other models. Validation methodologies suggested by Judkoff (1988), which include: analytical verification, empirical validation, and comparative testing.

In 1995, the IEA BESTEST was developed in conjunction with the International Energy Agency (IEA) as a valid procedure for testing a model's ability to model the building envelope, and providing detailed diagnosis of sources of disagreement among models (Judkoff and Neymark 1995c). The BESTEST procedure has also been adopted by the ASHRAE Standard 140: Method of Test for Evaluation of Building Energy Analysis Computer Programs (ASHRAE 2001a, 2004, 2007c, 2011).

At the same time, the Home Energy Rating System BESTEST, called HERS BESTEST, was developed to test simplified tools such as those used for home energy rating systems (Judkoff and Neymark 1995a, 1995b). A revised version of the HERS BESTEST was developed in 1997 for hot and humid climates, called the Florida-HERS BESTEST (Judkoff and Neymark 1997a, 1997b). In 2002, the HVAC BESTEST was developed to test a model's ability to model mechanical equipment (Neymark and Judkoff 2002). HVAC BESTEST was later updated in 2004 (Neymark and Judkoff 2004). Finally in 2010, a BESTEST for existing homes, called BESTEST-EX, was developed (Judkoff et al. 2010). BESTEST-EX is a procedure for testing the reliability of residential simulation models that predict retrofit energy savings, including their associated calibration methods and uncertainty ranges for selected inputs (Judkoff et al. 2011).

2.5.1.2 Automation of Building Energy Simulations

Since numerous inputs containing the building information need to be collected to run a simulation, several efforts have been made to simplify a simulation for homeowners. The LBNL provides a simplified web-based whole-building energy simulation, called Home Energy Saver (HES) (LBNL 2008). The HES requires minimum users' inputs for a simulation, and unknown inputs are automatically provided by the database that created from variety of sources, including: the Residential Energy Consumption Survey (RECS), the Gas Appliance Manufacturers Association (GAMA), the Air Conditioning, Heating, and Refrigeration Institute (AHRI), the Association of Home Appliance Manufacturers (AHAM) and so on. The HES uses DOE-2.1e building simulation program for energy calculations, and provides energy use and energy-related emissions, energy bills and potential energy savings for a typical house in that region as a simulation result.

Marshall et al. (2009, 2010) also created an energy efficiency calculator, called AIM (Assess, Improve, and Measure), using a minimum number of parameters for the whole-building hourly energy simulation. In the AIM calculator, most inputs that a homeowner may not know are filled-in using statistical tables based upon the age of the house. For example, window U-value, roof and wall insulation, and other systems information are automatically provided using statistical data that represents a fusion of information from several sources, including: the 2000 and 2006 IECC (ICC 2000, 2006) for building energy code values during 2001-2005 and 2006 onwards, respectively, the NAHB housing survey data (1997-2004) for wall and ceiling insulation and window type during 1997-2004 for East Texas and West Texas (NAHB 2005), the ASHRAE Fundamentals for U-value and SHGC of windows for window types (ASHRAE 1997), LBNL's Home Energy Saver for HVAC and DHW system efficiencies (Mills 2007).

2.5.2 Data-driven Method

The *data-driven method* uses measured energy use to describe the building and HVAC system, and estimate the building and HVAC system performance parameters (Haberl and Culp 2009). The related literature reviewed in this section uses categories of the *data-driven method* that was defined by ASHRAE (ASHRAE 2009).

2.5.2.1 Empirical or "Black-Box" Approach

The PRInceton Scorekeeping Method (PRISM) and the ASHRAE Inverse Modeling Toolkit (ASHRAE IMT) are representative models that use the *data-driven method*. *Data-driven methods* are useful empirical models to analyze building energy use such as for calculating pre- and post-savings from energy conservation retrofits. The variable-based degree-day method in PRISM and the ASHRAE IMT are discussed in the next section.

2.5.2.1.1 History of the PRInceton Scorekeeping Method (PRISM)

In 1980s, the PRISM was developed by Goldberg (1982) and Fels (1986). PRISM is a variable-based degree-day (VBDD) model for weather-normalizing monthly energy use. The algorithm in the VBDD model finds a base-temperature that gives the best statistical fit between energy use and the number of the degree days in each energy use period. PRISM was developed to measure retrofit energy savings in residential building. PRISM has been widely used since its creation. For example, Rodberg (1986) used PRISM to analyze the results of energy conservation measures applied to low-income residences in New York City. Goldman (1986) used the PRISM to evaluate a low-income weatherization program for residences in Wisconsin. Goldman and Ritschard (1986) studied a complex of apartment buildings in San Francisco to test of the applicability of the PRISM to large multi-family buildings. The application to residential buildings has, subsequently, been extended to commercial buildings by Eto (1988). However, PRISM was found to not always be appropriate for all commercial buildings because the commercial buildings may have varying degrees of heating or cooling energy use above or below the change-point, which PRISM assumes in constant (Rabl 1986; Kissock 1993). Therefore, Schrock and Claridge (1989), and Ruch and Claridge (1992) developed a four-parameter change-point model for commercial buildings, which uses a search algorithm to find the optimal change-point ambient temperature by searching within an interval known to contain the change-point temperature.

2.5.2.1.2 History of the ASHRAE Inverse Modeling Toolkit (ASHRAE IMT)

The ASHRAE IMT is a FORTRAN 90 application for calculating linear, change-point linear, multi-linear, variable-based degree-day, and combined change-point linear and regression models (Kissock et al. 2002). Several of the change-point models in the IMT came from EModel (Kissock 1993).

In the 1990s, EModel was developed by Kissock (1993), which integrated algorithms from several previous models. EModel used the algorithms of one- and two-parameter single-variable and multi-variable regression models from Press et al. (1986), and a modified version of the four-parameter change-point multi linear model from studies performed by Schrock and Claridge (1989), and Ruch and Claridge (1992).

In 2002, Kissock (Kissock et al. 2002) developed the ASHRAE IMT using the algorithms from EModel and additional algorithms from other models, which include a five-parameter change-point model, a combination of change-point, multi-variable regression, and a VBDD multi-variable regression model. The accuracy of the ASHRAE IMT was proven by performing accuracy and precision tests as part of the testing for ASHRAE Research Project 1050-RP (Kissock et al. 2002; Haberl et al. 2003; Haberl and Cho 2004).

2.5.2.1.3 Description of single-and multi-variable models in the ASHRAE Inverse Modeling Toolkit (ASHRAE IMT)

This section describes single-and multi-variable models in the ASHRAE IMT, including one, two, three, four and five-parameter single-variable models, and multi-variable regression models (MVR). The "one-parameter or constant model" is a model where the energy use is constant over a given period, which is appropriate for analyzing buildings that use energy weather-independently.

The "two-parameter model" is appropriate for analyzing buildings in extreme climates (i.e., artic or tropical climates), which operate an HVAC system for heating or cooling continuously year-round. In addition, the two-parameter model is used for buildings with dual-ducts, single-fan, constant-volume systems without economizers, and the constant-use domestic hot water system, which are based on the water supply temperature (Haberl and Cho 2004).

The “three-parameter model”, which includes a change-point linear and variable-based degree-day models, are appropriate for analyzing a wide range of building types such as residential buildings, small commercial buildings, and buildings that use gas served by boiler thermal plants (Haberl and Cho 2004).

The “four-parameter model” is appropriate for analyzing buildings that have variable-air-volume HVAC heating systems depending on the ambient temperature, or for analyzing whole-building electricity use of grocery stores that have large refrigeration loads and significant cooling loads during the cooling season (Kissock et al. 2003).

The “five-parameter model” is appropriate for analyzing whole-building energy use in buildings with air conditioning and electric heating, or weather-dependent performance of the electricity use of variable-air-volume systems. This model describes an increase in energy use below the change-point associated with heating, an increase in energy use above the change-point associated with cooling, and constant energy use between the heating and cooling change-points (Kissock et al. 2003).

The “day-adjusted model” is used with one, two, three, four and five parameter linear or change-point linear monthly utility models, where the energy use per period is divided by the days in the billing period before the regression is performed. The day-adjusted model is similar to other models except that the final coefficient of the model is shown by an energy use per day, which is then multiplied by the number of days in the billing period to adjust for variations of the utility billing cycle. In addition, Haberl and Cho (2004) showed that the accuracy of the regression model for case-study residence improved by using a day-adjusted model from 0.78 to 0.83 of R^2, and an improvement in the CV (RMSE) from 24.0% to 19.5% comparing to the unadjusted monthly model.

Finally, the multi-variable regression (MVR) models are an extension of single-variable models added more independent variables into the models of building energy use. The goal of modeling the multi-variable models of building energy use is to characterize the building energy use with a few readily available and reliable independent variables. The independent variables should be selected such that they are not affected by the change from pre- to post-retrofit periods, such as environmental variables, including outdoor dry-bulb temperature, solar radiation, and outdoor specific humidity (ASHRAE 2009).

2.5.2.1.4 Empirical or "Black-box" approach used for predicting the energy conservation measures

Several studies have been conducted for predicting the effectiveness of energy conservation measures (Hallinan et al. 2011, Kissock and Mulqueen 2008, and Raffio et al. 2007). Kissock and Mulqueen (2008) analyzed the utility bills and weather data from hospital buildings to target and measure the effectiveness of energy efficiency opportunity. First, electricity and natural gas uses from the monthly utility bills were regressed against outdoor dry-bulb temperature using the PRISM. They then used TMY2 data instead of typical weather data and three-parameter change-point PRISM model for the regressions. Interpretations of coefficients derived from three-parameter PRISM models of electricity and natural gas uses were performed to identify important parameters for predicting energy efficiency opportunities. The coefficients for the three-parameter change-point PRISM model included a weather-independent energy use, heating or cooling change-point temperature, and heating or cooling slope. Similar studies were also performed using different type of buildings such as single-family residences (Hallinan et al. 2011, Raffio et al. 2007).

2.5.2.2 Calibrated Simulation Approach

2.5.2.2.1 Calibrated simulation methodologies

Several calibrated simulation methodologies have been categorized and summarized well by Reddy (2005). According to Reddy, calibrated simulation methodologies are divided into four groups, which include: calibration based on manual, iterative, and pragmatic intervention; calibration based on a suite of informative graphical comparative displays; calibration based on special tests and analytical procedures; and analytical/mathematical methods of calibration. In this study, Reddy's groups will be modified and categorized as followings: (1) Calibration based on a manual and iterative intervention, (2) Calibration based on graphical displays and statistical analysis, and (3) Calibration based on special tests and analytical procedures.

2.5.2.2.1.1 Calibration based on a manual and iterative intervention

The manual and iterative intervention methods have been the most popular approach for the calibrated simulation. In this approach, a calibrated simulation of an existing building is obtained from the simulation user's past experience by adjusting input parameters iteratively and comparing the results with the building's utility data, walk-through audits, and short-term monitoring of the buildings.

One of the first studies about calibrated simulation was in the late 1970s by Diamond and Hunn (1981). They gathered detailed information about the seven sets of commercial buildings, including HVAC systems, operating schedules, and monthly utility data for an entire year. Next, they simulated the buildings using DOE-2 and compared the results with the monthly utility data to verify the DOE-2 simulation. They concluded that the composite standard deviation for the set of seven buildings on monthly basis was 18.7 percent for electric use and 26.3 percent for gas use.

A few years later, Kaplan et al. (1990a, 1990b) studied calibrated simulation with small office buildings. They tried to calibrate the DOE-2.1c model with monitoring data from short periods: three days for a hot period, a cold period, and in between the heating and cooling seasons. They suggested that for the calibration procedure, one of the first things to do is to correct the obvious simulation errors such as unreasonable default values emphasized by the simulation outputs, then correct internal loads and other inputs (i.e., infiltration, weighting factors, etc.). They achieved a calibration that closely matched the monitored data in both monthly end-use total and daily average end-use profiles.

In a similar fashion, Hunn et al. (1992) calibrated the DOE-2.1d model for the Texas Capitol building. First they analyzed measured electricity use of the building by weekdays, Saturday and Sunday. Next, they generated normalized electricity use schedules for typical day types for the building. They found that the typical weekday, Saturday and Sunday electricity use schedules could achieve successful calibration of an hourly simulation model of the building.

About this same time, Norford et al. (1994) and Lunneberg (1999) also pointed out the importance of the internal load for a reliable calibration in office buildings through the case studies. Norford et al. (1994) suggested three steps of a calibration procedure: calibrating internal loads first, then the HVAC schedules and thermostat settings, and finally the HVAC and building envelope performance, in that order.

Shortly after that, Bou-Saada and Haberl (1995a, 1995b) and Haberl and Bou-Saada (1998) studied the calibrated simulation of weather-dependent loads (i.e., space heating and cooling). They developed a procedure for disaggregating whole-building electricity into hourly end-uses. In this procedure the monitored hourly whole-building electricity was grouped into weekdays and weekends first, then grouped into three day types depending on the daily dry-bulb temperature: less than 45°F, from 45°F to 75°F, and more than 75°F (i.e., six end-use categories: heating, cooling, and non-heating/non-cooling for weekdays and weekends). After that, they produced a weather-independent end-use disaggregation using on-site surveys and sub-meters to provide information about lights and plug loads. The weather-dependent end-use were then separated based on days when the outdoor temperature was less than 45°F (heating) or more than 75°F (cooling). The range in between the heating and cooling ranges energy use was attributed to end-use HVAC fan use. Through this procedure, the weather-dependent loads were calibrated.

In addition, the impact of differential weather data on the simulation result was studied. Haberl et al. (1995) evaluated the impact of using measured weather data for a DOE-2 simulation of a large institutional building. They compared the simulation results of using Typical Meteorological Year (TMY) weather data with those of using measured data or Test Reference Year (TRY) weather data, and found that the simulation results using the TRY weather data considerably improved the cooling energy simulation, but not the heating energy simulation.

2.5.2.2.1.2 Calibration based on graphical displays and statistical analysis

Graphical displays and statistical analysis methods for calibrated simulation have also been developed. These methods were used to show the differences between the simulated and measured energy use using monthly and diurnal graphical plots and statistical indices to help simulation users in deciding which parameters to calibrate for the next iteration (Reddy 2005).

The most useful plots in calibrated simulations are as followings: carpet plots, three-dimensional plots, superimposed and juxtaposed binned, box whisker and mean (BWM) plots in addition to the standard two-dimensional plots, such as scatter plots and time-series plots, contoured density plots, and time sequenced surface density plots for graphical plots.

Bronson et al. (1992) and Haberl et al. (1993b) developed, and evaluated comparative three-dimensional graphics for a case-study building. The comparative three-dimensional graphics were a useful visual tool for the calibrated simulation of weather-independent loads (i.e., lights and equipment) because they visually highlighted patterns in the hourly differences between the simulated and measured energy use. The method allowed the simulation users to quickly recognize patterns in the comparisons of the calibration, such as over-predictions in the spring and fall mornings and afternoons throughout the year. The carpet plots, on the other hand, proved useful for the calibrated simulation on weather-dependent loads by detecting different trends between the DOE-2 simulated and measured energy use. The carpet plots they developed were a combination of plots that proved useful for the calibration on weather-dependent loads, including an hourly scatter plot of energy use vs. ambient temperature, a "mapping" of the energy use onto a psychrometric chart, histograms showing the occurrences of data on the psychrometric chart in both temperature and specific humidity bins, energy use vs. specific humidity, day-type plots, and time series traces of all variables (Haberl et al. 1995).

In addition, binned plots that were modified from indices developed by Abbas (1993), were developed that used superimposed and juxtaposed binned box-whisker-mean plots displaying the maximum, minimum, mean, median, 10^{th}, 25^{th}, 75^{th}, and 90^{th} percentile points for each data bin for a given period of data (Bou-Saada and Haberl 1995a, 1995b; Haberl and Bou-Saada 1998). The binned plots effectively showed how well a model was calibrated at a specific temperature bin. The method allowed simulation users to view and analyze the weather-dependent and weather-independent hourly energy use. Haberl et al. (1993a, 1996) also developed other plots to help calibrated simulations such as the contoured density plots of energy use that can provide the users an improved perception of the central tendency of a cloud of data points, and time-sequenced, surface density plots of energy use that added time sequencing of the contoured density plots of energy use. These graphical displays have been evaluated in several case studies, and have proven to significantly help improve the calibrated simulation models.

Several statistical analysis methods have also been used to quantify the accuracy of calibrated simulation. The most used statistical indices to date are Mean Bias Error (MBE), and Coefficient of Variation of the Root Mean Square Error (CV (RMSE)). In 1993, the competition, called “the Great Energy Predictor Shootout” was held (Kreider and Haberl 1994a, 1994b). The results were announced at the Denver ASHRAE seminar which showed the most accurate method for making hourly energy use predictions based on limited amounts of measured data. The next year in 1994, the second competition, the Great Energy Predictor Shootout II (Haberl and Thamilseran 1996, 1998), was also held by ASHRAE to select the most accurate method for measuring savings from energy conservation retrofits. In both competitions the MBE and the CV (RMSE) were used as standard statistical indices. The competitions showed that the best achievable hourly CV (RMSE) was in the range between 10% and 20%. In addition, tolerance of the CV (RMSE) using hourly data has been published in several guidelines as well. The acceptable calibration tolerance of the hourly CV (RMSE) in ASHRAE Guideline 14-2002 (ASHRAE 2002) is 30%, in IPMVP (IPMVP 2002) it is 20%, and in FEMP (U.S.DOE 2008b) it is 30%.

2.5.2.2.1.3 Calibration based on special tests and analytical procedures

Special test and analytical procedures are specialized approaches for calibrated simulation, including short-term energy monitoring (STEM) test and signature analysis method as described below.

2.5.2.2.1.3.1 Short-Term Energy Monitoring (STEM) tests

The short-term energy monitoring (STEM) test was developed by Subbarao et al. (1988) for a case-study residential building in Virginia. They set up the instrumentation to measure a small number of data channels and monitored the building energy performance for three days. Then, the analysis of the data provided an extrapolation to the long-term performance. Manke and Hittle (1996) also conducted short-term energy monitoring for small commercial buildings. In their study, they calibrated the BLAST simulation model using parameter sensitivity tests (i.e., changing values of the model parameters to achieve a best fit to the measured energy use). They used the Root Mean Squared Error (RMSE) and total building energy use over the test period to compare the model to the energy use. First, they identified four or five primary building parameters (i.e., Wall and roof R value, window transmittance and internal mass surface area and thickness) that would be most influential to the building energy performance, and then changed the parameter values one at a time from 10% to 200% of their nominal values in increments of 10% while holding the other parameters constant, and calculated the RMSE for each sensitivity runs. The calibration process started with the parameter with the lowest RMSE, and varied the next best parameter until a minimum RMSE was reached. The process was continued with each parameter until a global minimum was reached. As a result through the application of the method to a case-study building, the calibrated BLAST model had a substantially improved agreement with the measured building energy performance data. They also discovered that final values of the parameters varied a great deal from the nominal values of the parameters.

2.5.2.2.1.3.2 Signature analysis method

The signature analysis method using calibration signatures and characteristic calibration signatures was developed as one of the calibrated simulation methods. It mainly focused on heating and cooling loads that have been the major issue for the calibrated simulation studies. The calibration signatures are normalized plots of the difference between measured heating or cooling energy use values and corresponding simulated values as a function of dry-bulb temperature or other independent parameters. The method was developed by Wei et al. (1998) based on the previous efforts from Liu and Claridge (1998), and Katipamula and Claridge (1993) for providing simulation users significant information about the input parameters change needed to achieve calibration. A few years later, Liu et al. (2003, 2004) added characteristic calibration signatures in the calibration process.

Characteristic calibration signatures are parametric sensitivity analysis plots that are helpful in the determination of which simulation input parameter needs to be adjusted and by what amount. Characteristic calibration signatures are also normalized plots like the calibration signatures. However, they have two simulated heating or cooling energy uses. One is for the energy use from a baseline model that uses a nominal input value. The other one is for the energy use from an adjusted model, which uses an adjusted input value of a particular input parameter. To determine which parameter value needs to be adjusted, shapes of characteristic calibration signatures and calibration signatures need to be compared. If the shape of characteristic calibration signatures is well matched with the shape of calibration signatures, the adjusted particular parameter is the one that needs to be calibrated.

For example, parameters adjusted for the characteristic calibration signatures are as follows: cold deck temperature, hot deck temperature for DD systems, supply air flow rate for CV systems, minimum air flow rate for VAV systems, floor area, preheat temperature, internal gains, outside air flow rate, room temperature, envelope U values, and economizer. Since the characteristic calibration signatures provide important information about the input variable change, simulation users can use the graphics to make quick and rational decisions during calibrating the model.

2.5.2.2.1.4 Automation of calibrated simulations

Several methodologies for developing an automated calibrated simulation were studied, including: Lee and Claridge (2002), Sun and Reddy (2006) and Baltazar (2006).

Lee and Claridge (2002) calibrated an office building automatically based upon the “Simplified Energy Analysis Procedure” of Knebel (1983) using commercial optimization software. The procedure for the automatic calibration is a global optimization process minimizing the error between measured and simulated energy use (i.e., chilled water use and hot water use) using a statistical index, RMSE. In this study, they adjusted five-parameter values, including cooling coil leaving temperature, room temperature, heat transfer rate for the building envelope, supply air volume, and outside air flow fraction, for the calibrated calibration to achieve the best optimization.

Sun and Reddy (2006) proposed a general analytic framework for calibrating an office building energy simulation through mathematical and statistical basis using DOE-2 program. The methodology is consisted of four sequential sub-analyses, including a sensitivity analysis to identify a subset of strong influential parameters, identifiable analysis to determine how many parameters of this subset can be tuned mathematically and which specific ones are the best candidates, numerical optimization to minimize the difference between simulated output and measured data and to estimate strong parameters, and uncertainty analysis using Monte Carlo method to deduce the range of variation of these parameters. Through the methodology, they calibrated the office building simulation using three parameters, including minimum supply airflow, energy efficiency ratio and wall U factor as the most suitable parameters, and concluded that their proposed analytical calibration method was able to predict measured monthly energy use well.

Baltazar (2006) also developed an automated calibration methodology for building energy simulation, and the methodology is based on the “Simplified Energy Analysis Procedure” of HVAC systems. His automated calibration was performed by minimizing the total RMSE ($RMSE_T$) that is composed with addition of heating and cooling RSME between the measured and simulated energy use over daily conditions. He first adjusted one simulation parameter from 1 percent to 200 percent of five parameters, including heat transfer coefficient, number of people, outside air fraction, VAV minimum air flow fraction and hot deck temperature variation, while the other parameters were held at the nominal values. Through the simulations of the parameters, the parameter value that has the minimum $RMSE_T$ was identified, and calibration was performed by holding the identified parameter's value and repeating the set of the simulations previously performed for the next adjustments of the other parameter values. This procedure was repeated until the $RMSE_T$ minimum is less than or equal to the accuracy criterion established. However, since this procedure was a time-consuming process, the Golden Section search was used to find the minimum $RMSE_T$ for each parameter, which uses same procedure described previously but uses numerical search technique. After that, a non-canonical optimization algorithm, the Simulated Annealing technique was performed by finding the global optimum for automation of the calibration.

2.5.2.3 Physical or "Gray-Box" Approach

Recently, a *data-driven method* has been used as one of the methods to calibrate simulation. The *data-driven method* is capable of accurately capturing as-built energy use, and allows for accurate prediction of future use under certain circumstances because the model parameters are deduced from actual building use (ASHRAE 2009). To calibrate the simulation using the *data-driven method*, simulated energy use and monthly utility bills of building need to be regressed first by statistical programs such as the PRISM or the ASHRAE IMT. After that, important parameters that may affect to the calibration need to be identified by comparing the two models, and adjusting simulated energy use to closely match monthly utility bills. The *data-driven method* used for calibrated simulation has been conducted by Yoon and Lee (2003).

Yoon and Lee (2003) calibrated their simulation using a *data-driven method*. They suggested seven steps for their data-driven calibration procedure using a case-study commercial building in Seoul, South Korea. They calibrated their simulation using monthly utility bills, on-site visits, and monitored data. At first, they simulated the building using DOE-2.1e, and disaggregated the weather-independent loads and weather-dependent loads using three-parameter change-point regression model for electricity and natural gas uses. Then, they calibrated the weather-independent loads for mid-season in April by modifying the input values of the simulation, including lighting and equipment power density and their operating schedule for weekdays and weekends to match with monitored data of the building for the period. After that, they calibrated weather-dependent loads by tuning the HVAC input values, including heating and cooling equipment's efficiency, and part load performance. They could finally achieve the calibrated simulation with 3.6% for annual electricity and 22.7% for annual natural gas of CV (RMSE), respectively.

2.6 Summary of the Literature Review

The literature review presented an analysis of several topics relevant to the current work, including: building energy codes; code compliance software for residential buildings; the residential or Home Energy Rating System (HERS) in the United States; home energy audits, including energy conservation measures for the building envelope, electrical and lighting systems and HVAC systems; a review of measurement and verification methods for measuring energy savings; and a review of different types of energy estimating and modeling methods in terms of *forward* and *data-driven methods*. The findings of the literature review are summarized below.

- Summary of review for building energy codes, including code compliance software for residential buildings and Home Energy Rating System (HERS) in the United States

The building energy codes, including history of the building energy code, code compliance software for residential buildings and Home Energy Rating System (HERS) in the United States was reviewed in this section. The establishment of building energy codes has begun since the energy crisis occurred in 1973. The energy crisis of 1973 accelerated energy efficiency requirements to building energy codes throughout the United States. At first, the United States government established a number of policies to reduce energy demand by improving of the energy efficiency of buildings, and energy related technical societies responded to those policies by publishing standards such as the ASHRAE Standard 90, 90.1, 90.2 and the IECC. Today, most states in the United States have adopted the IECC and ASHRAE Standards as their residential building energy codes respectively. Additionally, in the U.S. code compliance software has been developed to check compliance with the energy standards for residential programs. The software programs reviewed for residential buildings include: REScheck™ developed by the U.S. DOE; EnergyGauge® USA by the FSEC; IC3 by the ESL and others. In addition, the Home Energy Rating System (HERS) developed by RESNET was reviewed.

- Summary of review for building energy audits, including the home energy audits procedure and energy conservation measures

The home energy audits, including the home energy audits procedure and energy conservation measures (ECM) were reviewed in this section. The original home energy audit has begun in the 1970s using the form of a checklist that an energy auditor could use to perform a walk-through examination of residences. The auditor noted the problems of the building on the checklist and delivered it to the homeowner. Since then, the home energy audits procedure has been developed, and the procedure is composed of several details nowadays. The detailed home energy audits procedure starts by collecting information about a building envelope, operation, systems and utility bills. These data are then analyzed to determine how energy is used, and what needs to be changed to reduce future energy use in the building. After that, selected changes (i.e., ECMs) are proposed and evaluated by assessing the energy savings and cost-effectiveness of each measure. The ECMs for houses in terms of the building envelope, electrical systems, and HVAC systems were reviewed as well.

- Summary of review for measurement and verification methods of measuring energy savings

The measurement and verification methods of measuring energy savings were reviewed in this section. The measurement and verification (M&V) is a process for quantifying retrofit energy savings delivered by the ECMs. The standardized M&V

procedure in the ASHRAE Guideline 14-2002 was reviewed for commercial buildings, and PRISM methods that is a well-known method for the M&V in residential since 1980s was reviewed for residential buildings.

- Summary of review for energy estimating and modeling methods: *Forward method*

One of energy estimating and modeling methods, *forward method* was reviewed in this section. According to 2009 ASHRAE Handbook of Fundamentals, the *forward method* was defined as the method using known physical description of the building, HVAC systems and plant equipment to calculate the building energy use. Whole-building energy simulation programs such as DOE-2.1e, eQUEST and EnergyPlus are the representative examples of the *forward method*.

A literature review was conducted regarding whole-building energy simulation programs. This included a review of the BESTEST series, which is a systematic testing procedures for the simulation programs, including IEA BESTEST, HERS BESTEST, Florida-HERS BESTEST, HVAC BESTEST, and BESTEST-EX. Additionally, automated or simplified simulation models that have been developed were reviewed as well such as the AIM calculator, which is an easy-to-use web-based program for homeowners. The AIM calculator uses minimum number of parameters for the building energy simulation by filling-in the unknown parameters with statistical information.

- Summary of review for energy estimating and modeling methods: The *data-driven method*, includes empirical or “Black-Box” approach, calibrated simulation approach, and physical or “Gray-Box” approach

One of energy estimating and modeling method, *data-driven method* was reviewed in this section. According to 2009 ASHRAE Handbook of Fundamentals, the *data-driven method* was defined as the method using measured energy use to describe the building and HVAC system, and estimating building and HVAC system parameters. The *data-driven method* can be classified into three categories, including empirical or "Black-Box" approach, calibrated simulation approach, and physical or "Gray-Box" approach.

The related literature review was conducted regarding the *data-driven method* according to the ASHRAE defined categories. The empirical or "Black-Box" approach is usually appropriate for evaluating the impact of energy conservation measures in an actual building using statistical regression models such as the PRISM or the ASHRAE IMT. The calibrated simulation approach can also be used to evaluate energy conservation measures. It uses building energy simulation program and tunes the simulated energy use to closely match the measured energy use by adjusting various parameters of the program. The calibration process can be divided into three groups: calibration based on manual and iterative procedures, calibration based on graphical displays and statistical analysis, and calibration that uses special tests and analytical procedures. The manual and iterative intervention methods have been the most popular approach for calibrated simulation, but this requires a high level of skill from the simulation user and special knowledge about the building and its HVAC systems.

The graphical displays and statistical analysis methods show the visual differences between the simulated and measured energy use using monthly and diurnal plots and statistical indices. Such information is helpful to users in deciding which parameters to calibrate for the next iteration. In addition, special tests and analytical procedures such as the short-term energy monitoring (STEM) tests and signature analysis methods have been used successfully for calibration. Methodologies for automated calibration were reviewed as well. For the automation of the calibration, statistical indices have been used as boundary values to determine the adequacy of the calibration levels. The last approach reviewed was the *data-driven method,* is a physical or “Gray-Box” approach. The approach first formulates a physical model of the building and HVAC system then, identifies important parameters, using aggregated physical parameters and characteristics by statistical analysis. Finally, the physical or “Gray-Box” approach was reviewed, which has also been used as one of the methods to calibrate simulations.

CHAPTER III

SIGNIFICANCE AND LIMITATIONS OF THE STUDY

3.1 Significance of the Study

This study is significant because it seeks to develop and test an easy-to-use, semi-automated residential audit methodology for analyzing single-family residential energy use in hot and humid climates. The methodology is expected to be helpful to users who have little expertise in building energy simulations, as well as by expert residential energy auditors who need to estimate where the energy is being inefficiently used, and to determine what needs to be fixed more accurately and quickly in a residential building.

3.2 Limitations of the Study

This study has the following limitations:

1) The study is focused on single-family detached houses only in hot and humid climates,
2) The study is focused on one-story, slab-on-grade, single-family detached houses with gas furnace for the heating and a residential air-conditioning system for the cooling systems, and
3) The study is focused on developing a semi-automated audit methodology which builds on the existing ESL DOE-2 simulation program (DDP),
4) A simple pay-back calculation does not include maintenance expenditure.

CHAPTER IV

METHODOLOGY

This chapter describes the methodology used in this study. The goal of this methodology is to provide an accurate, consistent and easy-to-use, semi-automated home energy audit procedure to quickly and accurately identify improvements in energy efficiency in an existing single-family house in a hot and humid climate. In order to accomplish this, three sequential methodologies were developed: 1) a methodology to enable the use of an easy-to-use residential simulation for a user who is not familiar with building energy simulation and HVAC systems or other residential systems; 2) a methodology that enables a semi-automatic, calibrated simulation using monthly utility bills for accurate predictions of the savings from energy-efficient retrofits of a house; and 3) a methodology for determining the potential savings from energy conservation measures using the calibrated simulation.

The overall procedure for the semi-automated home energy audits developed in this study is shown in Figure 4.1. A detailed description for each step will be described in the corresponding sections in this chapter.

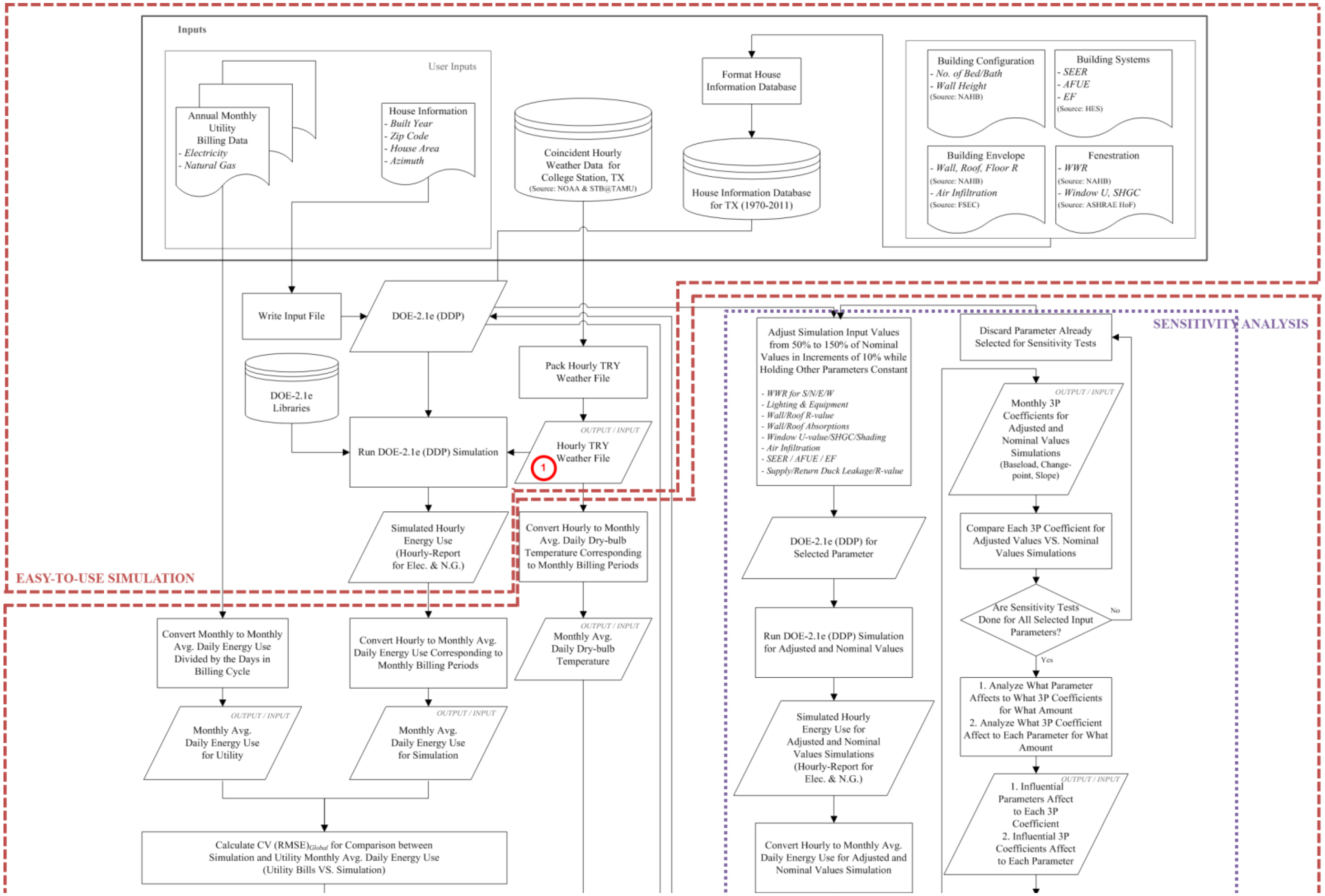

Figure 4.1 Overall Semi-automated Home Energy Audits Methodology

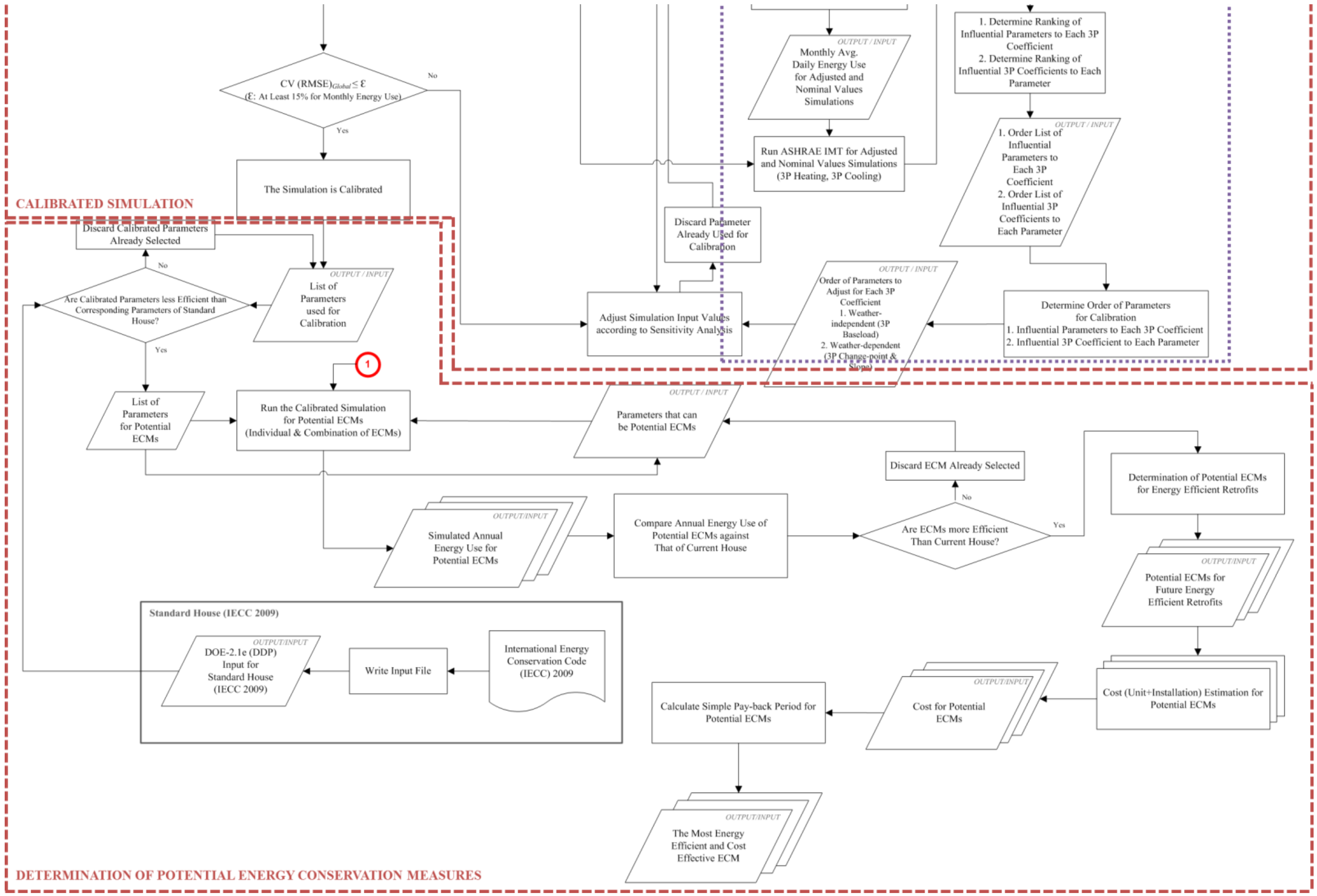

Figure 4.1 Continued

4.1 Development of a Methodology for an Easy-to-use Simulation

This study uses the Desktop DOE-2 Processor (DDP)[2] developed by the ESL for examination of historical energy use of an existing house as the first step of the home energy audits procedure. In order to run the DDP, a number of simulation input parameters need to be entered by the user. The parameters include: building envelope information, as well as HVAC and other system information. However, most of simulation users who are either homeowners or builders are not familiar with these inputs. Therefore, an easy-to-use simulation was developed in this study so users with no previous knowledge of simulation could perform on accurate simulation. This methodology builds on the previous study called AIM (Marshall et al. 2010)[3], and Figure 4.2 shows the easy-to-use simulation input information, which consists of: 1) user input, 2) coincident hourly weather data and 3) the house information database.

4.1.1 User Input

Using this procedure, the user can employ the easy-to-use simulation with limited information that is commonly available during a real estate transaction and the twelve monthly utility bills for the house. The user is required to input the year the house was constructed, the total floor area of the house, the azimuth of the house and the zip code of the address where the house is located. When the user enters the year the house was built, floor area, azimuth and location of the house, the corresponding statistical building input values of the house will be filled-in from the established house

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[2] A detailed description for the DDP (Desktop DOE-2 Processor) is described in Section 2.1.2.4.
[3] A detailed description for the AIM (Assess, Improve, and Measure) is described in Section 2.5.1.2.

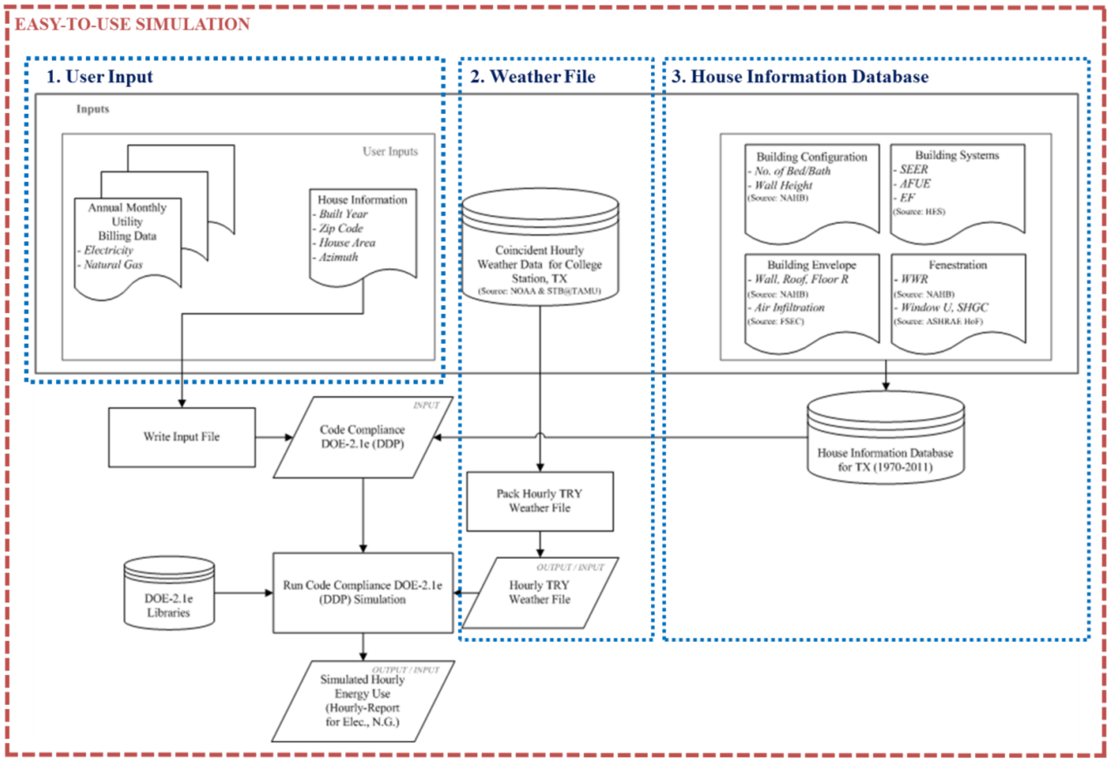


Figure 4.2 Inputs for an Easy-to-use Simulation

information database based upon the age and location of the house. The house information database will be described in detail in section 4.1.3. In addition, the utility bills of the house for twelve months will be used for a calibration of the house simulation. Details for the calibrated simulation will be described in section 4.2.

4.1.2 Coincident Hourly Weather Data

In order to run an hourly simulation of a residence, an hourly weather file needs to be available that contains the appropriate weather data. For example, Typical Meteorological Year 2 (TMY2) format weather files are recommended for use for selecting adequate HVAC systems or estimating energy use of the building for normal weather conditions since the TMY2 is annual averaged data composed of twelve typical meteorological months for a location for a thirty-year history from 1961 to 1990 (Marion and Urban 1994). On the other hand, Test Reference Year (TRY) format weather files are recommended for use to represent the actual weather data that corresponds to a specific utility billing period. Therefore, a TRY weather file is recommended for use for calibrating a building energy simulation against actual energy use data for a particular year.

In this study, TRY format weather files were used for the calibrated simulation. Since the case-study houses in this study are located in College Station and Plano, Texas, the TRY format weather files for both locations were produced that corresponded to the billing period[4].

The following hourly weather parameters must be contained in the TRY file:

- Dry-bulb temperature in °F
- Wet-bulb temperature in °F
- Dew-point temperature in °F
- Wind speed in knots
- Wind direction in degrees (0°=North, 90°=East, 180°=South and 270°=West)
- Global solar radiation in Btu/hr-ft^2
- Direct normal solar radiation in Btu/hr-ft^2
- Precipitation in inches
- Station pressure in inHg

[4] TRY weather data for College Station and Dallas, Texas are shown in Appendix D.

The hourly weather parameters, including dry-bulb temperature, wet-bulb temperature, dew-point temperature, wind speed and direction, precipitation and station pressure were obtained from the National Climatic Database Center (NCDC) website (NCDC 2012). The global solar radiation was obtained from the Texas Commission on Environmental Quality (TCEQ) website (TCEQ 2012) and the solar test bench on the roof of the Langford A Architecture Center at Texas A&M University. The direct normal solar radiation was obtained from either a calculation that uses the measured global solar radiation, or from measurements from the normal incidence pyrtheliometer (NIP) located on the solar test bench. The calculation for the direct normal solar radiation will be explained in the Appendix E. In addition, hourly weather data obtained from the NCDC, the TCEQ and solar test bench at Texas A&M University sometimes has missing data, and the missing data of certain weather parameters needs to be filled-in before packing the weather file. In order to do that, the method suggested by Long (2006) was applied in this study, and it will be explained in the Appendix E as well.

The collected hourly weather parameters were then arranged as shown in Figure 4.3 with the required TPE file format as shown in Table 4.1 (Buhl 1999). After generating the TPE file, an INP weather file was also created. The INP file was arranged as shown in Figure 4.4 according to a required format as shown in Table 4.2 (Buhl 1999). Then the TPE and the INP files were packed to the TRY weather file using DOE-2 weather processor in DOE-2.1e program. The DOE-2 weather processor is a command program. The function of the weather processor is to read hourly weather data in a variety of formats, extract the data required by DOE-2 as entering "*doe2wth_(TPE file* *name)*” on the command window, and write a packed binary weather file which will be used by the DOE-2.1e simulation program (Buhl 1999).

1	2	3	4	5	6	7		8	9		10	11	12	13
03904	042	039	035	340	017	300	20999999999999999999999999999999999	0004	0000		2010	01	01	00
03904	041	038	034	340	013	300	30999999999999999999999999999999999	0004	0000		2010	01	01	01
03904	040	037	033	330	013	300	50999999999999999999999999999999999	0004	0000		2010	01	01	02
03904	037	034	029	330	012	300	60999999999999999999999999999999999	0003	0000		2010	01	01	03
03904	035	033	028	340	011	300	60999999999999999999999999999999999	0003	0000		2010	01	01	04
03904	034	032	028	010	009	300	30999999999999999999999999999999999	0003	0000		2010	01	01	05
03904	033	031	028	310	005	300	80999999999999999999999999999999999	0003	0000		2010	01	01	06
03904	032	030	027	310	005	301	10999999999999999999999999999999999	0003	0000		2010	01	01	07
03904	032	030	027	340	009	301	30999999999999999999999999999999999	0025	0000		2010	01	01	08
03904	034	031	026	330	009	301	40999999999999999999999999999999999	0077	0317		2010	01	01	09
03904	036	032	027	010	007	301	60999999999999999999999999999999999	0131	0299		2010	01	01	10
03904	040	035	028	010	006	301	40999999999999999999999999999999999	0171	0292		2010	01	01	11
03904	044	037	029	350	009	301	10999999999999999999999999999999999	0196	0287		2010	01	01	12
03904	048	039	029	040	005	300	60999999999999999999999999999999999	0196	0267		2010	01	01	13
03904	050	040	026	050	007	300	30999999999999999999999999999999999	0173	0223		2010	01	01	14
03904	051	040	023	020	007	300	10999999999999999999999999999999999	0134	0166		2010	01	01	15
03904	052	040	022	060	006	300	10999999999999999999999999999999999	0075	0059		2010	01	01	16
03904	050	039	023	070	004	300	00999999999999999999999999999999999	0018	0002		2010	01	01	17
03904	048	038	022	070	003	300	20999999999999999999999999999999999	0001	0000		2010	01	01	18
03904	047	037	022	000	000	300	30999999999999999999999999999999999	0002	0000		2010	01	01	19
03904	046	037	023	000	000	300	50999999999999999999999999999999999	0002	0000		2010	01	01	20
03904	046	037	024	000	000	300	40999999999999999999999999999999999	0002	0000		2010	01	01	21
03904	044	036	025	050	004	300	50999999999999999999999999999999999	0002	0000		2010	01	01	22
03904	044	036	026	000	000	300	40999999999999999999999999999999999	0002	0000		2010	01	01	23

1	Station Number	8	GHSR (Btu/ft2-hr)
2	T_{db} (°F)	9	DNSR (Btu/ft2-hr)
3	T_{wb} (°F)	10	Year
4	T_{dp} (°F)	11	Month
5	Wind Direction (Deg.)	12	Day
6	Wind Speed (Knots)	13	Hour
7	Station Pressure (inHg)		

Figure 4.3 An Example of the TRY_TPE File

```
PACK
T_CLL 2010
TRY    03904  -999     6 30.6  96.3 30-BITSOLAR      4 20.   0.025       13
0.55  0.52  0.54  0.51  0.47  0.45  0.42  0.42  0.42  0.48  0.56  0.56
-999.
LIST
PACKED  -999  -999     1    12
END
```

Figure 4.4 An Example of the TRY_INP File

Table 4.1 Explanation of Contents for the TPE File (Buhl 1999)

File Field Number	Columns	Element	Example
001	01 - 05	STATION NUMBER	44444
002	06 - 08	DRY-BULB TEMPERATURE	65
003	09 - 11	WET-BULB TEMPERATURE	63
004	12 - 14	DEW POINT TEMPERATURE	62
005	15 - 17	WIND DIRECTION	180
006	18 - 20	WIND SPEED	010
007	21 - 24	STATION PRESSURE	2970
008	25	WEATHER	0
009	26 - 27	TOTAL SKY COVER	00
010	28 - 29	AMOUNT OF LOWEST CLOUD LAYER	99
011	30	TYPE OF LOWEST CLOUD OR OBSCURING PHENOMENA	9
012	31 - 33	HEIGHT OF BASE OF LOWEST LAYER	999
013	34 - 35	AMOUNT OF SECOND CLOUD LAYER	99
014	36	TYPE OF CLOUD - SECOND LAYER	9
015	37 - 39	HEIGHT OF BASE OF SECOND LAYER	999
016	40 - 41	SUMMATION AMOUNT OF FIRST TWO LAYERS	99
017	42 - 43	AMOUNT OF THRID CLOUD LAYER	99
018	44	TYPE OF CLOUD - THIRD LAYER	9
019	45 - 47	HEIGHT OF BASE OF THIRD LAYER	999
020	48 - 49	SUMMATION AMOUNT OF FIRST THREE LAYERS	99
021	50 - 51	AMOUNT OF FOURTH CLOUD LAYERS	99
022	52	TYPE OF CLOUD - FOURTH LAYER	9
023	53 - 55	HEIGHT OF BASE OF FOURTH LAYER	999
024	56 - 59	SOLAR RADIATION[a]	0000
025	60 - 69	BLANK	
026	70 - 73	YEAR	1999
027	74 - 75	MONTH	01
028	76 - 77	DAY	01
029	78 - 79	HOUR	00
030	80	BLANK	

[a]The DOE-2 weather processor recognizes the following solar data in TRY format:
Columns 57-59 Total horizontal radiation in Btu/ft^2-hr
Columns 61-63 Direct normal radiation in Btu/ ft^2-hr

Table 4.2 Explanation of Contents for the INP File (Buhl 1999)

PACK

line 1: The word PACK in columns 1-4.

line 2: The station name in columns 1-20. This name will be written on the output file as identification. The entry here is for the user only and is arbitrary.

line 3: The data is entered as shown below. When the format is shown as L, it signifies that the datum must be left justified in the columns indicated. The format R signifies that the datum must be right justified in the columns indicated, and the format D means that the value should be entered with a decimal point (neither right or left justification is required). For those with FORTRAN background: L corresponds to A6, R to I6, and D to F6.1.

Example of how the data is entered (line 3)

Columns	Format	Description
1 - 6	L	A code-word specifying the unpacked file type. Options are TMY2, WYEC2, CD144, CD144Sa,TRY, TRYSLMa, TD9685, and OTHERb.
7 - 12	R	Weather station number. This is required.
Note: for TMY2 files, the following inputs on line 3 may be left blank		
13 - 18	R	The year of the weather data (e.g., 1999). This is required for CD144 and TD9685 files (which can contain several years of weather data). For other files, –999 should be input.
19 - 24	R	Time zone (as in the SITE-PARAMETERS command)
25 - 30	D	Latitude (degrees). Positive north of the equator, negative south of the equator.
31 - 36	D	Longitude (degrees). Positive west of Greenwich, negative east of Greenwich.
37 - 42	L	A code-word specifying the number of bits per word to be used in packing the output file. The options are 60-BIT or 30-BIT (for 32-bit machines)
43 - 48	L	A code-word specifying the type of output file. The options are NORMAL and SOLAR. NORMAL produces a DOE-2 weather file with no solar data. SOLAR produces a file containing solar information.
49 - 54	R	Interpolation interval. The program fills in missing data by linear interpolation between the last and the next value present, if the number of hours of missing data is less than or equal to the interpolation interval. If more hours of data are missing than the interpolation interval, it still does interpolation up to 24 hours and a warning message is issued. If more than 24 hours are missing, the previous value is used. The interpolation interval must be less than 24c.
55 - 60	D	This sets the maximum dry-bulb temperature change allowed in one hour. Changes larger than this will cause a warning message to be printed.
61 - 66	D	Soil thermal diffusivity (ft2/hr). Used for calculating monthly ground temperatures. A value of 0.010 can be used for dry soil, 0.025 for average soil, and 0.050 for wet soil.
67 - 72	D	Station altitude (feet), used in CD144 and TD9685.
73 - 78	R	Location needed only for CD144S and TRYSLM to choose a cloud cover model. See ILOC. Used only for CD144 and TRY formats. Select the location that best represents the data being packaged.

[a] CD144S tells the weather processor to read a file in CD144 format and add ersatz solar data using the ASHRAE clear sky model, SOLMET cloud cover regressions formula, and the Erbs-Klein-Duffie direct/diffuse model. TRYSLM does the same for data in TRY formats.

[b] If OTHER is chosen, the data should either be in the DOE-2 measured weather data format (see Processing Nonstandard Weather Data) or a special OTHER processing subroutine must be written and installed in the weather processor. To accomplish the latter, the you must have the source code and a FORTRAN compiler.

[c] The weather processor makes no evaluation of the data to see that it is internally consistent, except that during interpolation it never allows the wet-bulb temperature to exceed the dry-bulb temperature, or the dew point temperature to exceed the wet-bulb temperature.

Table 4.2 Continued

ILOC and Station Name			
01 ALBUQUERQUE, NM	08 CHARLESTON, SC	15 GREAT FALLS, MT	21 NEW YORK, NY
02 APALACHICOLA, FL	09 COLUMBIA, MO	16 LAKE CHARLES, LA	22 NORTH OMAHA, NE
03 BISMARCK, ND	10 DODGE CITY, KS	17 MADISON, WI	23 PHOENIX, AZ
04 BOSTON, MA	11 EL PASO, TX	18 MEDFORD, OR	24 SANTA MARIA, CA
05 BROWNSVILLE, TX	12 ELY, NV	19 MIAMI, FL	25 EATTLE-TACOMA
06 CAPE HATTERAS, NC	13 FORT WORTH, TX	20 NASHVILLE, TN	26 WASHINGTON, DC
07 CARIBOU, ME	14 FRESNO, CA		

line 4: Contains the 12 clearness numbers (one per month) in D format in column intervals 1-6, 7-12, 13-18, etc. (skip for TMY2; unused for WYEC2, so can be just 1.0). See 1993 ASHRAE Fundamentals, p. 27.12.

line 5: Contains the 12 ground temperatures (one per month in F) in D format in column intervals 1-6, 7-12, 13-18, etc. (skip for TMY2). A value of –999 will flag the program to calculate the ground temperature using the method of Kusuda and Achenbach (ASHRAE Trans. 41 (1965) p. 61).

4.1.3 House Information Database

I created a house information database to better facilitate the easy-to-use simulation in this study. The house information database automatically provides the users with guestimates of residential building characteristics that are needed by the simulation based upon the year the house was constructed and the location of the house (i.e., zip code). However, this house information database is limited to averaged-sized, single-family houses and house locations in Texas or similar climates (Marshall et al. 2010). The house information database is kept as a Microsoft Excel spreadsheet, and linked to the DDP spreadsheet input. Since statistical input parameters are used in the easy-to-use simulation instead of actual parameter values, the simulation results may have some discrepancies with the actual energy use of a house. Therefore, the result of the easy-to-use simulation needs to be calibrated with actual energy use (i.e., monthly utility billing data for electricity and natural gas), which will be explained in section 4.2.5.

In order to create the house information database for Texas, the relevant residential building characteristics from 1970 to 2011 were collected or interpolated for certain periods, including: 1) general information of the house such as number of bed/bathrooms and wall height, 2) building envelope information such as wall, roof, floor R-values and air infiltration rate, 3) fenestration information such as window-to-wall ratio (WWR), window U-value and solar heat gain coefficient (SHGC), and 4) building systems information such as cooling systems efficiency (SEER), heating systems efficiency (AFUE) and hot water heater efficiency (EF). Each of residential building characteristic information will be described in following subsection.

The information in the database that will describe in the following subsections was compiled from a variety of sources, including, the National Association of Home Builders (NAHB) (NAHB 2012), 2009 ASHRAE Handbook of Fundamentals (ASHRAE 2009) and Home Energy Saver (HES) (Mills et al. 2007).

4.1.3.1 Residential Building Characteristics

- Number of bed/bathrooms

The average number of bed/bathrooms in a single-family house for East and West Texas from 1996 to 2011was obtained from the NAHB. Using an annual trend of number of bed/bathrooms for an extended period, average number of bed/bathrooms from 1970 to 1995 was compiled. As an improvement over AIM (Marshall et al. 2010), the number of bed/bathrooms from the NAHB from 1996 to 2011 was averaged again to mitigate the uneven values by a moving-average analysis. A moving-average analysis was generally used to determine the direction of the trend. In order to determine the trend of number of bed/bathrooms from 1996 to 2011, a 5-year moving-average was used as shown in Figure 4.5. For the last four years (i.e., 2008 to 2011), 4-year, 3-year, 2-year and 1-year moving-averages were used, respectively. The resultant number of bed/bathrooms from 1970 to 2011 is shown in Table 4.3 and Figure 4.6 (a) and (b).

Year	1996	1997	1998	1999	2000	2001	…	2008	2009	2010	2011
Moving Average Analysis Data Set (Number of bed/bathrooms)	1	2	3	4	5	6	…	13	14	15	16
	Data Set 1 (1996)							Data Set 13 (2008)			

Figure 4.5 An Example of a Moving-average Analysis for Number of Bed/bathrooms

- Wall height

The average wall height of a single-family house for East and West Texas from 1996 to 2011 was also obtained from the NAHB. In a similar fashion to number of bed/bathrooms, wall height from 1970 to 1995 was extrapolated, and wall height from 1996 to 2011 was averaged again using a moving-average analysis. The resultant wall height from 1970 to 2011 is shown in Table 4.3 and Figure 4.6 (c).

- Wall R-value

The average wall R-value of a single-family house for East and West Texas from 1997 to 2011was also obtained from the NAHB. In a similar fashion to number of bed/bathrooms, the wall R-value from 1970 to 1996 was extrapolated, and wall R-value from 1997 to 2011 was averaged again by a moving-average analysis. The resultant wall R-value from 1970 to 2011 is shown in Table 4.3 and Figure 4.7 (a).

- Roof R-value

The average roof R-value of a single-family house for East and West Texas from 1997 to 2011was obtained from the NAHB as well. In a similar fashion to number of bed/bathrooms, roof R-value from 1970 to 1996 was extrapolated, and roof R-value from 1997 to 2011 was averaged again by a moving-average analysis. The resultant roof R-value from 1970 to 2011 is shown in Table 4.3 and Figure 4.7 (b).

- Air infiltration rate

The air infiltration rate for a single-family house for 1970 thru 2008 was obtained from the values used in AIM (Marshall et al. 2009). The air infiltration rate after 2008 was extended from the previous year value (i.e., air infiltration rate for 2009 is same as the rate for the previous year, 2008). The resultant air infiltration rate from 1970 to 2011 is shown in Table 4.3 and Figure 4.7 (c).

- Window-to-wall ratio (WWR)

The average window-to-wall ratio (WWR) of a single-family house for

East and West Texas from 1997 to 2011 was calculated using the NAHB data. First, the average number of window units of a single-family house for East and West Texas was obtained from the NAHB, and then the window area was calculated with the assumption that the window is 5 feet in height and 3 feet in width. After that, window-to-wall ratio (WWR) was calculated from wall area, which was calculated from house area and wall height previously obtained, and window area of a house. In a similar fashion to number of bed/bathrooms, the WWR value from 1970 to 1996 was extrapolated, and the WWR value from 1997 to 2011 was averaged again by a moving-average analysis. The resultant WWR from 1970 to 2011 is shown in Table 4.3 and Figure 4.8 (a).

- Window U-value

Window U-values for a single-family house for East and West Texas from 1997 to 2011 were obtained from the NAHB data and the 2009 ASHRAE Handbook of Fundamentals (ASHRAE 2009). First, the percentage of the window type and glass type were looked up from the NAHB data; then, the adequate window U-value was found in the 2009 ASHRAE Handbook of Fundamentals. The window U-values from 1970 to 1996 were then obtained from the AIM (Marshall et al. 2009). The resultant window U-values from 1970 to 2011 are shown in Table 4.3 and Figure 4.8 (b).

- Solar heat gain coefficient (SHGC)

In a similar fashion to window U-value, the solar heat gain coefficient (SHGC) from 1997 to 2011 was also obtained from the NAHB data and the 2009 ASHRAE Handbook of Fundamentals (ASHRAE 2009).The SHGC values from 1970 to 1996 were obtained from the AIM (Marshall et al. 2009). The resultant SHGC values from 1970 to 2011 are shown in Table 4.3 and Figure 4.8 (c).

- Cooling system efficiency (SEER- Seasonal Energy Efficiency Ratio)

The average efficiency values for central air conditioner (SEER) of a single-family house throughout the U.S. from 1970 to 2003 were obtained from the Home Energy Saver (HES 2007), which originally came from the Air Conditioning and

Refrigeration Institute (ARI 2003), while the average efficiency from 2004 to 2008 was obtained from the AIM (Marshall et al. 2009). The average efficiency after 2008 was extended from the previous year's value (i.e., SEER for 2009 is same as SEER for the previous year, 2008). The resultant SEER values from 1970 to 2011 are shown in Table 4.3 and Figure 4.9 (a).

- Heating system efficiency (AFUE- Annual Fuel Utilization Efficiency)

The average efficiency values for gas furnace (AFUE) of a single-family house throughout the U.S. from 1970 to 2003 were obtained from the Home Energy Saver (HES 2007), which originally came from the Gas Appliance Manufacturers Association (GAMA 2003). The average efficiency values from 2004 to 2008 were obtained from the AIM (Marshall et al. 2009). The average efficiency values after 2008 were extended from the previous year's value (i.e., AFUE for 2009 is same as AFUE for the previous year, 2008). The resultant AFUE values from 1970 to 2011 are shown in Table 4.3 and Figure 4.9 (b).

- Hot water heater efficiency (EF- Energy Factor)

The averaged efficiency values for natural gas hot water heater (EF) of a single-family house throughout the U.S. from 1970 to 2005 were obtained from the Home Energy Saver (HES 2007), which originally came from the Gas Appliance Manufacturers Association (GAMA 2003), while the averaged efficiency values after 2005 were extended from the previous year's value (i.e., EF for 2006 is same as EF for the previous year, 2005). The resultant AFUE values from 1970 to 2011 are shown in Table 4.3 and Figure 4.9 (c).

Table 4.3 Summary of House Information Database

	General Information								Building Envelope					Fenestration							Systems		
	Source: NAHB												*Source: AIM*	*Source: NAHB*		*Source: NAHB, 2009 ASHRAE Handbook of Fundamentals and AIM*				*Source: Home Energy Saver and AIM*		
	House Area [ft^2]		**No. of Bedrooms [Units]**		**No. of Bathrooms [Units]**		**Wall Height [ft]**		**Wall R Value [ft^2-F-hr/Btu]**		**Roof R Value [ft^2-F-hr/Btu]**		**Air Infiltration [Normalized Leakage]**	**WWR [%]**		**Window U Value [Btu/ft^2-F-hr]**		**SHGC**		**Cooling System Efficiency [SEER]**	**Heating System Efficiency [AFUE]**	**Hot Water Heater Efficiency [EF]**
	East Texas	West Texas	East Texas	West Texas	East Texas	West Texas	East Texas	West Texas	East Texas	West Texas	East Texas	West Texas		East Texas	West Texas	East Texas	West Texas	East Texas	West Texas			
1970	2383	1933	3.7	3.4	3.7	3.9	8.5	8.8	2.73	2.73	19.00	19.00	0.67	24.2	26.1	1.27	1.27	0.75	0.75	6.50	60.00	47.4
1971	2384	1951	3.7	3.4	3.7	3.9	8.5	8.8	3.18	3.16	19.24	19.29	0.67	23.9	26.0	1.27	1.27	0.75	0.75	6.58	61.35	47.4
1972	2385	1969	3.6	3.4	3.6	3.9	8.5	8.8	3.55	3.55	19.40	19.60	0.67	23.6	25.8	1.27	1.27	0.75	0.75	6.66	62.70	47.4
1973	2386	1988	3.6	3.4	3.6	3.8	8.5	8.8	3.92	3.93	19.55	19.91	0.67	23.3	25.6	1.27	1.27	0.75	0.75	6.75	62.70	47.4
1974	2387	2006	3.6	3.4	3.6	3.8	8.5	8.8	4.29	4.31	19.70	20.22	0.67	23.1	25.4	1.27	1.27	0.75	0.75	6.85	62.70	47.4
1975	2388	2024	3.6	3.4	3.5	3.7	8.6	8.8	4.66	4.70	19.85	20.53	0.67	22.8	25.2	1.27	1.27	0.75	0.75	6.97	65.83	47.4
1976	2389	2042	3.6	3.4	3.5	3.7	8.6	8.8	5.03	5.08	20.00	20.84	0.67	22.5	25.1	1.27	1.27	0.75	0.75	7.03	66.12	47.5
1977	2390	2061	3.6	3.4	3.5	3.7	8.6	8.9	5.40	5.47	20.16	21.15	0.67	22.3	24.9	1.27	1.27	0.75	0.75	7.13	66.42	47.5
1978	2391	2079	3.6	3.4	3.4	3.6	8.6	8.9	5.77	5.85	20.31	21.47	0.67	22.0	24.7	1.27	1.27	0.75	0.75	7.34	66.71	47.6
1979	2392	2097	3.6	3.4	3.4	3.6	8.6	8.9	6.13	6.23	20.46	21.78	0.67	21.7	24.5	1.27	1.27	0.75	0.75	7.47	68.66	47.6
1980	2393	2115	3.6	3.4	3.4	3.5	8.6	8.9	6.50	6.62	20.61	22.09	0.60	21.5	24.3	1.27	1.27	0.75	0.75	7.55	70.60	47.7
1981	2394	2134	3.6	3.4	3.3	3.5	8.7	8.9	6.87	7.00	20.76	22.40	0.60	21.2	24.2	1.27	1.27	0.75	0.75	7.78	70.44	47.8
1982	2395	2152	3.6	3.4	3.3	3.5	8.7	8.9	7.24	7.39	20.92	22.71	0.60	20.9	24.0	1.27	1.27	0.75	0.75	8.31	70.28	47.9
1983	2396	2170	3.6	3.4	3.3	3.4	8.7	8.9	7.61	7.77	21.07	23.02	0.60	20.7	23.8	1.27	1.27	0.75	0.75	8.43	70.13	48.0
1984	2397	2189	3.6	3.4	3.2	3.4	8.7	8.9	7.98	8.15	21.22	23.33	0.60	20.4	23.6	1.27	1.27	0.75	0.75	8.66	72.62	48.1
1985	2399	2207	3.6	3.4	3.2	3.3	8.7	8.9	8.35	8.54	21.37	23.64	0.60	20.1	23.4	1.27	1.27	0.75	0.75	8.82	72.89	48.3
1986	2400	2225	3.6	3.4	3.2	3.3	8.7	8.9	8.72	8.92	21.52	23.95	0.60	19.8	23.3	1.27	1.27	0.75	0.75	8.87	73.73	48.4
1987	2401	2243	3.6	3.4	3.1	3.3	8.7	8.9	9.09	9.31	21.68	24.27	0.60	19.6	23.1	1.27	1.27	0.75	0.75	8.97	74.33	48.6
1988	2402	2262	3.6	3.4	3.1	3.2	8.8	9.0	9.46	9.69	21.83	24.58	0.60	19.3	22.9	1.27	1.27	0.75	0.75	9.11	74.86	48.8
1989	2403	2280	3.6	3.4	3.1	3.2	8.8	9.0	9.83	10.07	21.98	24.89	0.60	19.0	22.7	1.27	1.27	0.75	0.75	9.25	74.67	49.0
1990	2404	2298	3.5	3.4	3.0	3.1	8.8	9.0	10.20	10.46	22.13	25.20	0.44	18.8	22.5	1.27	1.27	0.75	0.75	9.31	76.70	49.2
1991	2405	2317	3.5	3.4	3.0	3.1	8.8	9.0	10.57	10.84	22.28	25.51	0.44	18.5	22.4	1.27	1.27	0.75	0.75	9.49	77.54	49.4
1992	2406	2335	3.5	3.4	3.0	3.1	8.8	9.0	10.94	11.23	22.43	25.82	0.44	18.2	22.2	1.27	1.27	0.75	0.75	10.46	82.08	49.6
1993	2407	2353	3.5	3.4	2.9	3.0	8.8	9.0	11.30	11.61	22.59	26.13	0.44	18.0	22.0	1.27	1.27	0.75	0.75	10.56	82.41	49.8
1994	2408	2371	3.5	3.4	2.9	3.0	8.9	9.0	11.67	12.00	22.74	26.44	0.44	17.7	21.8	1.27	1.27	0.75	0.75	10.61	82.43	49.9
1995	2409	2390	3.5	3.4	2.8	2.9	8.9	9.0	12.04	12.38	22.89	26.75	0.44	17.4	21.6	1.27	1.27	0.75	0.75	10.68	82.33	50.0

Table 4.3 Continued

	General Information								Building Envelope					Fenestration						Systems		
	Source: NAHB												*Source: AIM*	*Source: NAHB*		*Source: NAHB, 2009 ASHRAE Handbook of Fundamentals and AIM*				*Source: Home Energy Saver and AIM*		
	House Area [ft^2]		**No. of Bedrooms [Units]**		**No. of Bathrooms [Units]**		**Wall Height [ft]**		**Wall R Value [ft^2-F-hr/Btu]**		**Roof R Value [ft^2-F-hr/Btu]**		**Air Infiltration [Normalized Leakage]**	**WWR [%]**		**Window U Value [Btu/ft^2-F-hr]**		**SHGC**		**Cooling System Efficiency [SEER]**	**Heating System Efficiency [AFUE]**	**Hot Water Heater Efficiency [EF]**
	East Texas	West Texas	East Texas	West Texas	East Texas	West Texas	East Texas	West Texas	East Texas	West Texas	East Texas	West Texas		East Texas	West Texas	East Texas	West Texas	East Texas	West Texas			
1996	2412	2444	3.5	3.4	2.7	2.8	8.9	9.0	12.41	12.76	23.04	27.07	0.44	17.1	21.5	1.27	1.27	0.75	0.75	10.68	82.66	50.1
1997	2413	2463	3.5	3.4	2.7	2.8	8.9	9.1	13.50	13.91	23.48	28.00	0.44	16.3	20.9	1.23	0.79	0.75	0.69	10.66	82.86	50.1
1998	2415	2481	3.5	3.4	2.7	2.7	9.0	9.1	13.89	14.30	23.65	28.31	0.44	16.1	20.7	0.79	0.79	0.69	0.69	10.92	82.62	50.1
1999	2416	2499	3.5	3.4	2.6	2.7	9.0	9.1	14.26	14.68	23.80	28.62	0.44	15.8	20.6	0.79	0.79	0.69	0.69	10.96	82.63	50.1
2000	2417	2518	3.5	3.4	2.6	2.7	9.0	9.1	14.63	15.07	23.95	28.93	0.44	15.5	20.4	0.79	0.79	0.69	0.69	10.95	82.62	50.1
2001	2418	2536	3.5	3.4	2.6	2.6	9.0	9.1	15.00	15.45	24.11	29.24	0.44	15.3	20.2	0.79	0.79	0.69	0.69	11.07	83.15	50.1
2002	2419	2554	3.5	3.4	2.5	2.6	9.0	9.1	15.37	15.84	24.26	29.55	0.44	15.0	20.0	0.70	0.70	0.55	0.55	11.07	83.15	50.1
2003	2420	2572	3.5	3.5	2.5	2.5	9.0	9.1	15.74	16.22	24.41	29.87	0.44	14.7	19.8	0.70	0.70	0.55	0.55	11.07	83.15	50.1
2004	2421	2591	3.5	3.5	2.5	2.5	9.1	9.1	16.11	16.60	24.56	30.18	0.44	14.4	19.7	0.70	0.70	0.55	0.55	11.07	83.15	55.0
2005	2422	2609	3.5	3.5	2.4	2.5	9.1	9.1	16.48	16.99	24.71	30.49	0.44	14.2	19.5	0.70	0.64	0.55	0.55	11.07	83.15	55.0
2006	2423	2627	3.4	3.5	2.4	2.4	9.1	9.1	16.84	17.37	24.87	30.80	0.36	13.9	19.3	0.70	0.70	0.55	0.55	13.00	83.15	55.0
2007	2424	2645	3.4	3.5	2.4	2.4	9.1	9.1	17.21	17.76	25.02	31.11	0.36	13.6	19.1	0.70	0.70	0.55	0.55	13.00	83.15	55.0
2008	2425	2655	3.4	3.5	2.4	2.4	9.1	9.2	17.40	17.95	25.09	31.27	0.36	13.5	19.0	0.70	0.70	0.55	0.55	13.00	83.15	55.0
2009	2425	2664	3.4	3.5	2.3	2.3	9.1	9.2	17.58	18.14	25.17	31.42	0.36	13.4	18.9	0.47	0.70	0.49	0.55	13.00	83.15	55.0
2010	2426	2673	3.4	3.5	2.3	2.3	9.1	9.2	17.77	18.33	25.24	31.58	0.36	13.2	18.8	0.47	0.47	0.49	0.49	13.00	83.15	55.0
2011	2426	2682	3.4	3.5	2.3	2.3	9.1	9.2	17.95	18.53	25.32	31.73	0.36	13.1	18.8	0.47	0.47	0.49	0.49	13.00	83.15	55.0

Data from the NAHB, ASHRAE HoF and HES

Data from the AIM

Data extended from the previous data

Extrapolated data from the existing data

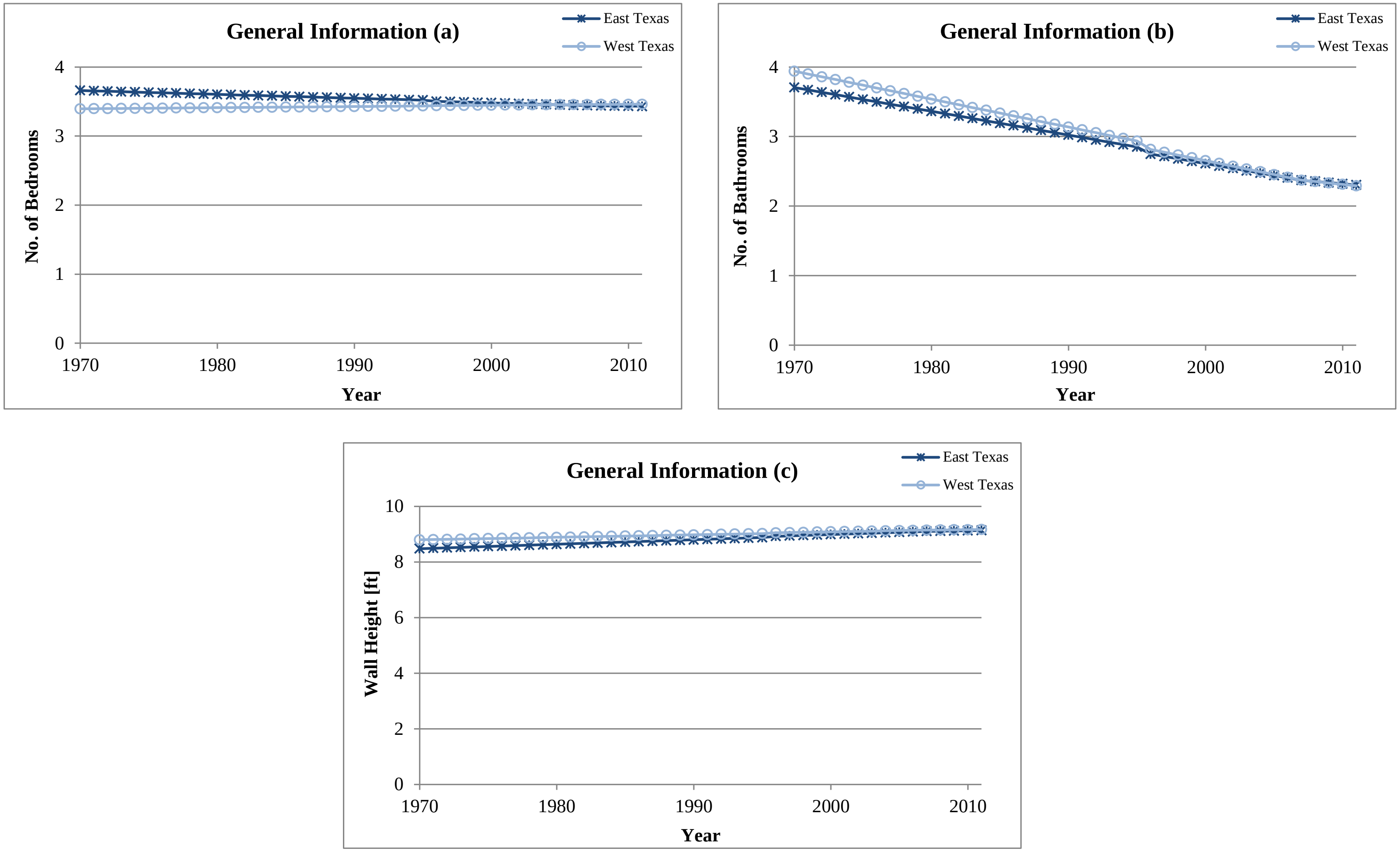
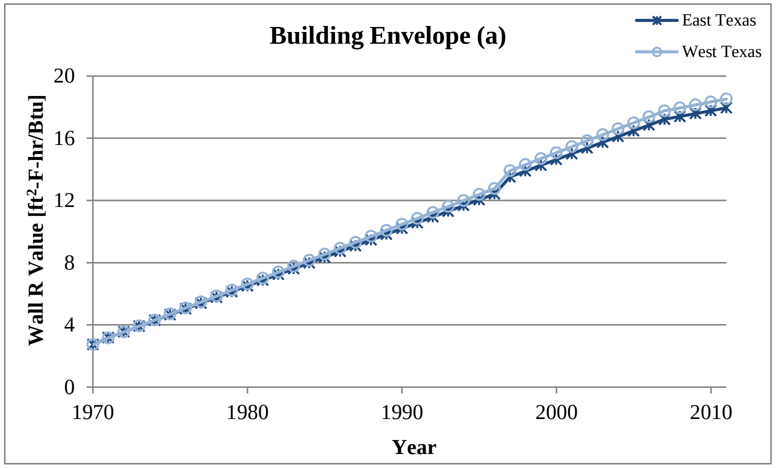
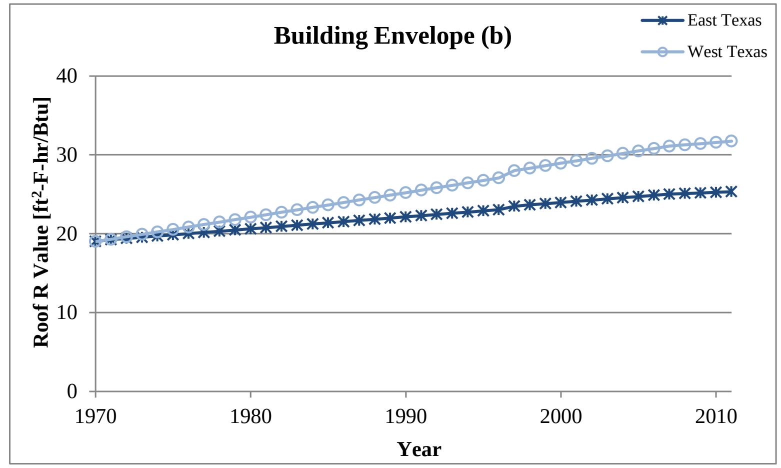


Figure 4.6 General Information of House Information Database: (a) Number of Bedrooms, (b) Number of Bathrooms and (c) Wall Height





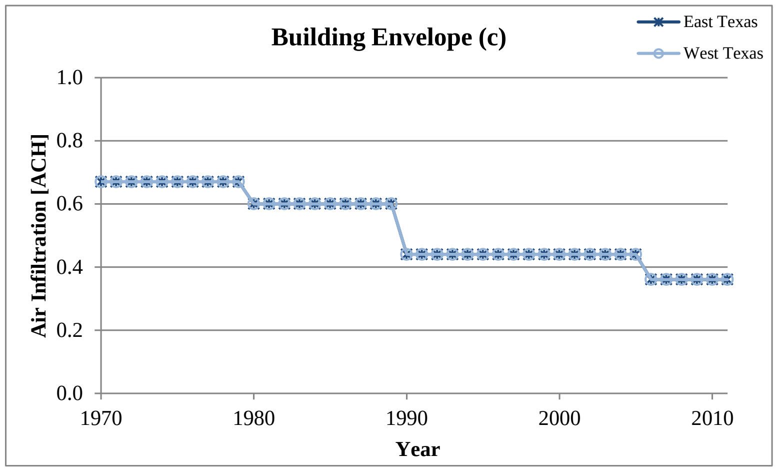


Figure 4.7 Building Envelope of House Information Database: (a) Wall R-Value, (b) Roof R-Value and (c) Air Infiltration

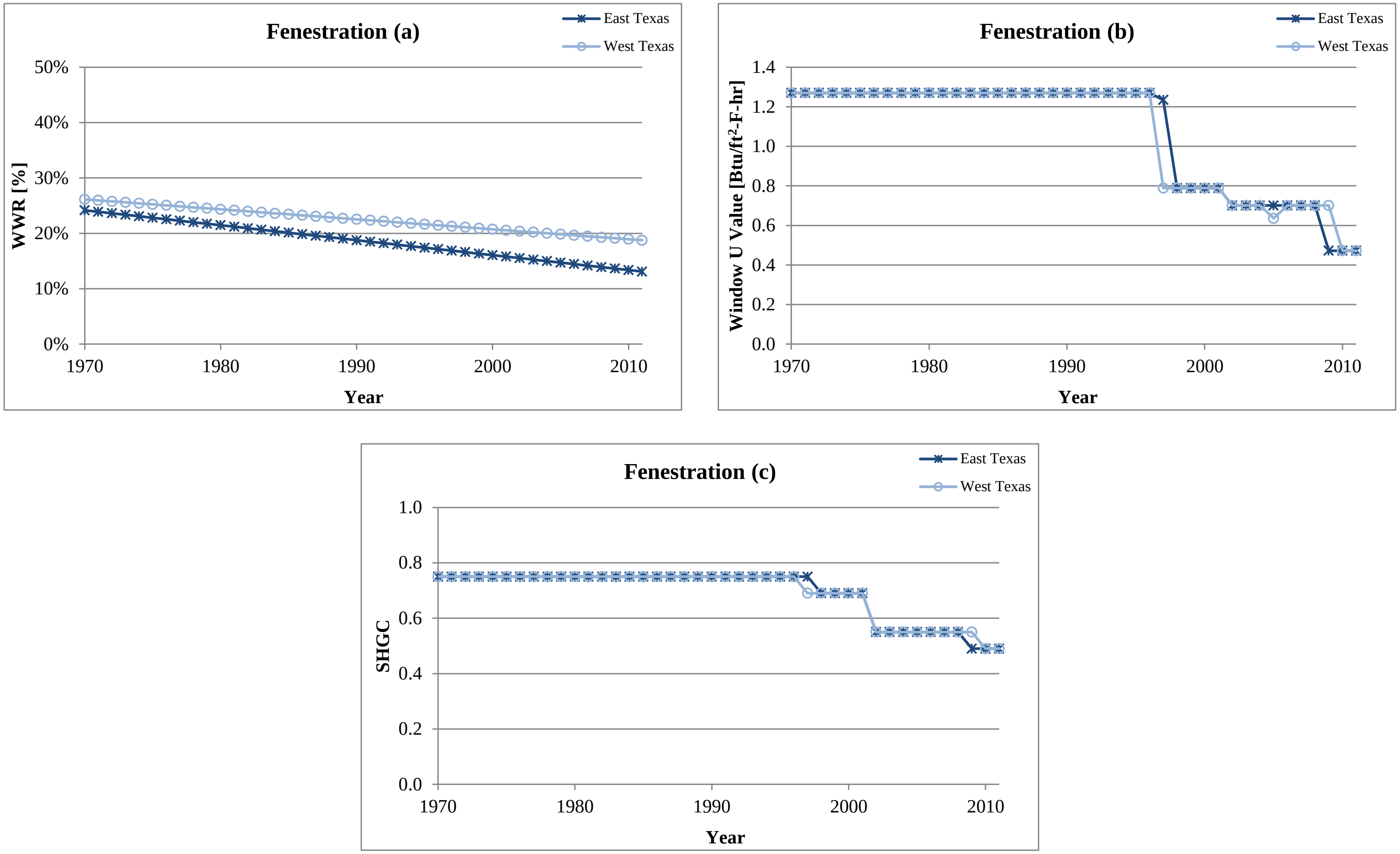


Figure 4.8 *Fenestration of House Information Database: (a) Window-to-wall ratio (WWR), (b) Window U-Value and (c) Solar Heat Gain Coefficient (SHGC)*

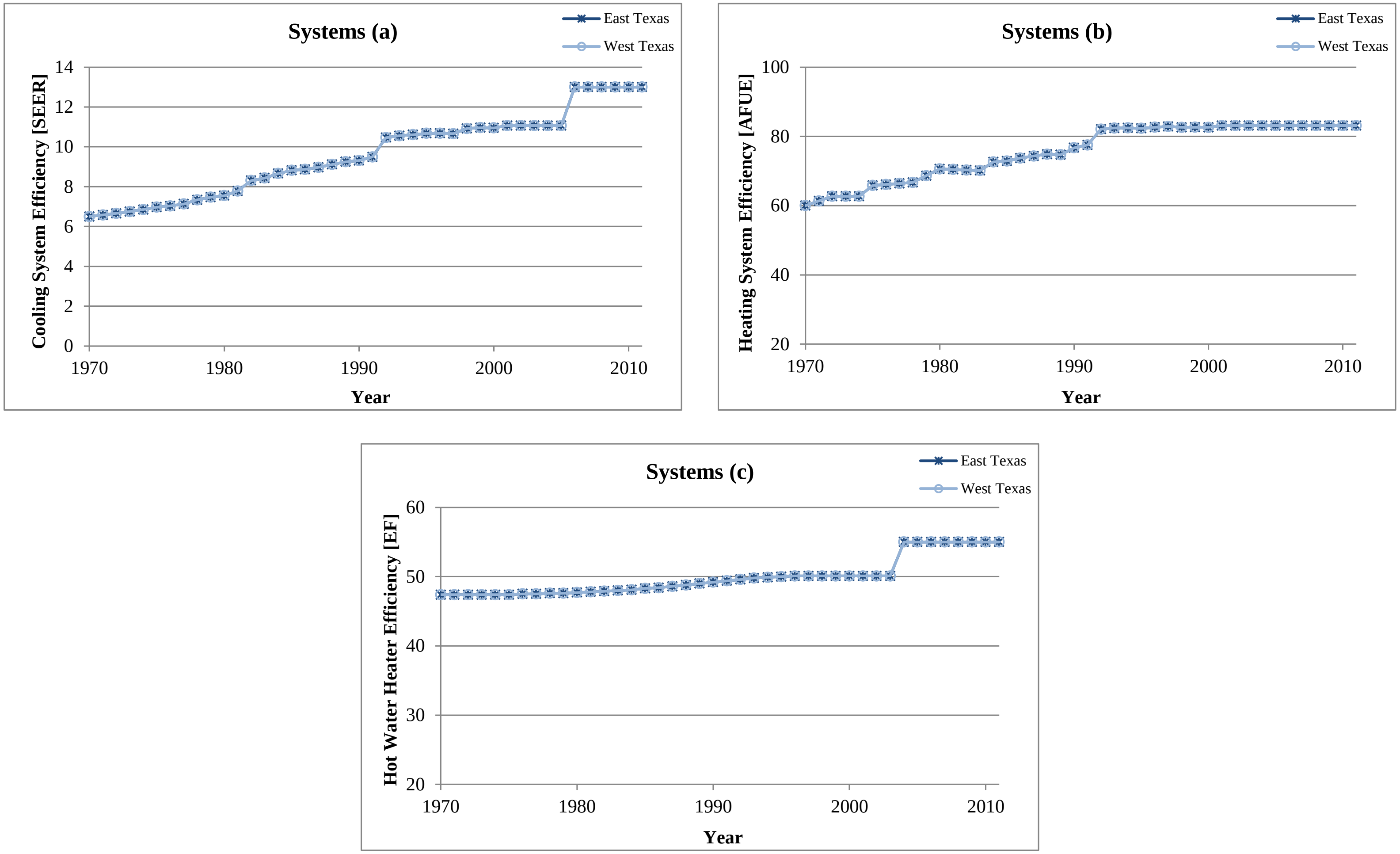


Figure 4.9 *Systems of House Information Database: (a) Cooling System Efficiency (SEER), (b) Heating System Efficiency (AFUE) and (c) Hot Water Heater Efficiency (EF)*

4.2. Development of a Methodology for a Semi-automatic Calibrated Simulation

In this study the easy-to-use simulation, DDP, used that contains a statistical database that was assembled from residential building characteristics constructed in Texas. Unfortunately, the simulated results may therefore have a discrepancy when compared with the energy use of the building. To adjust for this, the simulated building should be tuned by adjusting the appropriate input values to more closely match the actual building energy use to improve the credibility of the simulation. This process is commonly called a calibrated simulation. Calibrated simulation can predict more accurate energy savings for future energy efficiency retrofits of a building because the calibrated simulation can reflect a current building condition such as the deterioration of wall insulation and so on.

In this study, an improved methodology for calibrated simulation is proposed. This methodology can be automated because the calibration procedure was set by systematic rules. Therefore, the procedure is referred to as a semi-automatic calibrated simulation. Figure 4.10 shows the information flow of the semi-automatic calibrated simulation procedure. This section can be divided into five phases: 1) three-parameter change-point regression model; 2) the ASHRAE Inverse Modeling Toolkit; 3) applications of three-parameter change-point regression models to simulated building energy use and actual building energy use using the ASHRAE IMT; 4) sensitivity analysis using three-parameter change-point regression model; and 5) calibrated simulation. The first three subsections is an explanation about the three-parameter regression model and the statistical program which were used for the regression model in this study, as well as the application of the regression model to the simulated building energy use and actual building energy use, respectively. The next subsection will explain the energy analysis, which produces results that are used for the calibrated simulation. The last subsection will describe the methodology of semi-automatic calibrated simulation.

4.2.1 Three-parameter Change-point Regression Model

In this study, a physical or "Gray-Box" approach of the *data-driven method* was used for calibrated simulation. A more detailed explanation of the physical or "Gray-Box" approach of the *data-driven method* was described in Sections 2.4.2 and 2.5.2. To calibrate the simulation using the *data-driven method*, statistical regression programs including PRISM and the ASHRAE IMT were reviewed, and the ASHRAE IMT was chosen for use with this study.

The ASHRAE IMT (IMT) is a statistical toolkit for calculating linear, change-point linear, multi-linear, variable-based degree-day, and combined change-point linear regression models (Kissock et al. 2002). The IMT is mostly used for building energy analysis through weather-normalization. As described in previous Section 2.5.2, the three-parameter single-variable change-point linear regression model is appropriate for analyzing single-family residential energy use that is strongly influenced by outside weather conditions due to heat gain or heat loss through walls and windows, and air infiltration through the building surfaces. Thus, the three-parameter single-variable change-point linear regression model was used in this study for calibrated simulation since this study targets single-family residential energy use in hot and humid climates.

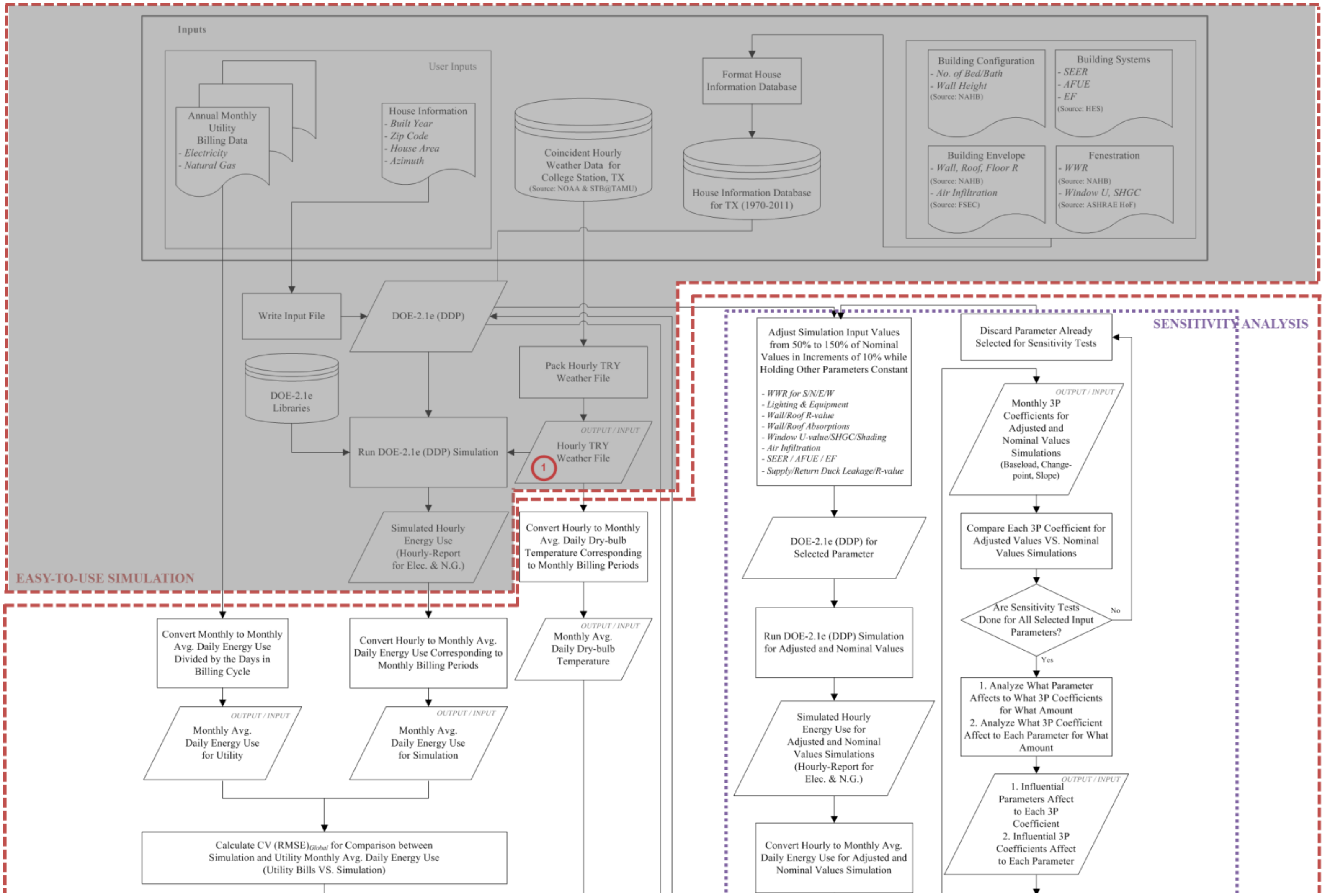


Figure 4.10 Procedure for Semi-automatic Calibrated Simulation

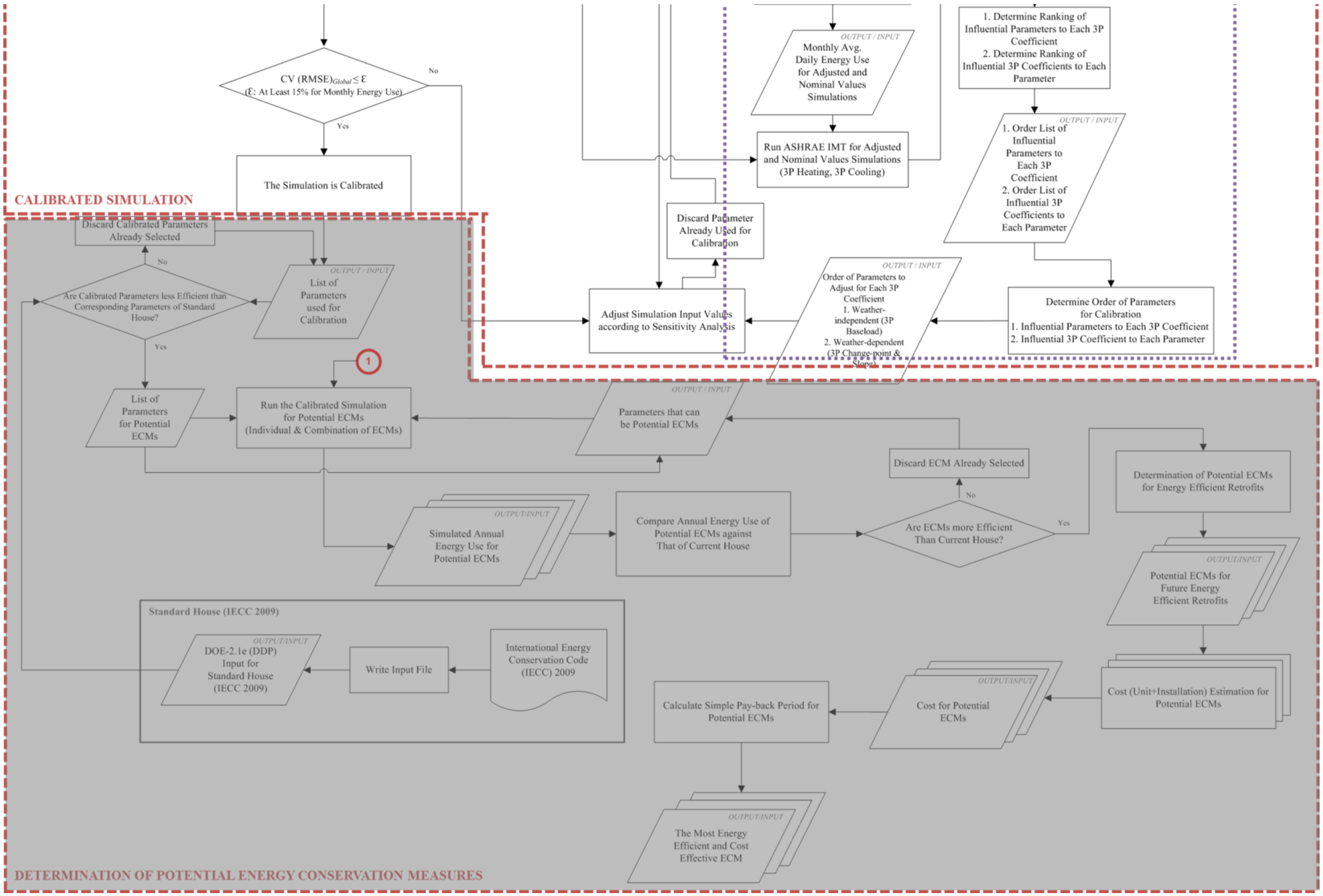


Figure 4.10 Continued

Figure 4.11 shows a typical three-parameter change-point linear model for (a) electricity use and (b) natural gas use of buildings that regressed building energy use as a function of outdoor temperature.

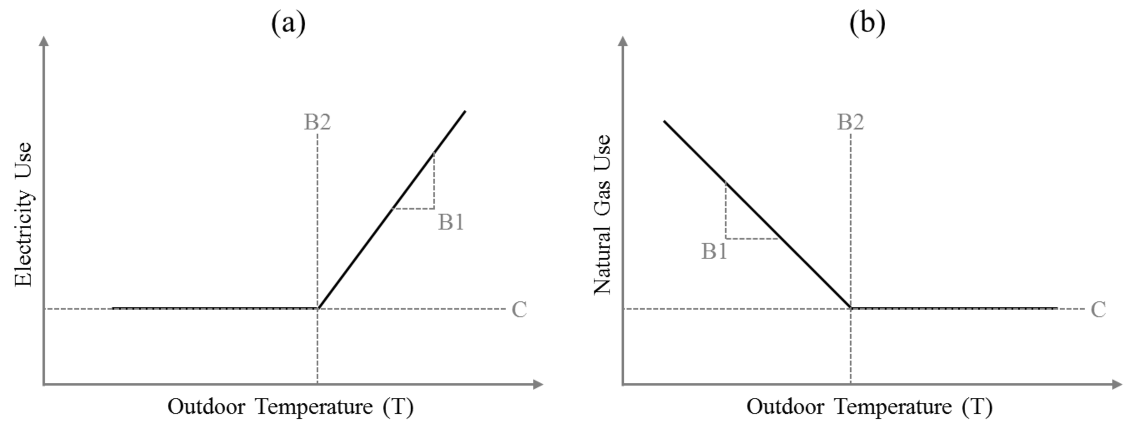


Figure 4.11 Three-parameter Change-point Linear Models for: (a) Electricity Use and (b) Natural Gas Use

Electricity use for a three-parameter change-point linear model of building can be calculated from equation (4.9). This equation describes the electricity use of a building as a constant, baseload or weather-independent load (*C* in Figure 4.11 (a)) until certain outdoor temperature, called cooling change-point temperature, is reached - *B2* in Figure 4.11 (a).When outdoor temperature is higher than the cooling change-point temperature, electricity use of a building increases with a linear slope, called the cooling slope (Figure 4.11 (a) or heating slope (Figure 4.11 (b)) or weather-dependent load, as seen in *B1* in Figure 4.11 for the three-parameter cooling (3PC) change-point model.

$$E = C + B1(T - B2)^{+} \tag{4.9}$$

Where *E* = Electricity use in kWh,

B1 = Cooling slope in $\frac{kWh}{°F}$ that describes the linear dependency on outdoor temperature,

B2 = Cooling change-point temperature in °F,

C = Baseload in kWh,

T = Outdoor temperature in °F, and

$(\ )^{+}$ = Positive values only inside the parenthesis.

One of the strengths of the 3PC change-point linear model is that the 3PC regression coefficients (i.e., *B1*, *B2* and *C* in equation (4.9)) characterize physical properties of the building envelop and operation of cooling system.

The 3PC coefficient *C* represents weather-independent electricity use used for a year-round such as lighting and equipment of the building. The 3PC coefficient *B1* represents weather-dependent electricity use that is used for cooling the building. This coefficient is related to cooling loads and cooling system efficiency of the building so that it can be expressed by equation (4.10). In this equation, since the sum of conductive heat gain through the building envelope and sensible heat gain through air infiltration account for a major portion of the cooling loads of the building, *CC* can be expressed by following equation (4.11). Lastly, the 3PC coefficient, *B2* is defined as the outdoor temperature when space cooling begins in the building. *B2* is a function of the cooling thermostat set-point temperature; the sum of the internal loads from electricity use, solar heat gain and occupants of the building; and heat transfer coefficient (i.e., *CC* in equation (4.11)) of the building envelope so that it can be expressed by equation (4.12) (Sever et al. 2011).

$$B1 = \frac{CC}{\eta_c} \tag{4.10}$$

$$CC = \left(\frac{A_{roof}}{R_{roof}} + \frac{A_{wall}}{R_{wall}} + \frac{A_{window}}{R_{window}} + \frac{A_{floor}}{R_{floor}}\right) + V \cdot \rho \cdot C_p \tag{4.11}$$

$$B2 = T_{csp} - \frac{Q_i}{CC} \tag{4.12}$$

Where η_c = Cooling system efficiency,

A = Area of heat transfer,

R = Building envelope resistance,

V = Air infiltration rate,

ρ = Air density,

C_p = Air specific heat,

T_{csp} = Cooling thermostat set-point temperature, and

Q_i = Internal loads.

In a similar fashion to the 3PC change-point linear model of the building, natural gas use using a three-parameter change-point linear model can be also calculated from equation (4.13). This equation divides the natural gas use of a building into three regions a constant, baseload or weather-independent load (*C* in Figure 4.11 (b)) when the outdoor temperature is higher than a certain outdoor temperature, called heating change-point temperature, *B2* in Figure 4.11 (b), and when the outdoor temperature is lower than the heating change-point temperature, the natural gas use of a building increases with certain slope, called heating slope or weather-dependent load, *B1* in Figure 4.11 (b). This type of model is called a three-parameter heating (3PH) change-point model.

$$E = C + B1(B2 - T)^{+} \tag{4.13}$$

Where *E* = Natural gas use in MMBtu,

B1 = Heating slope in $\frac{MMBtu}{°F}$ that describes the linear dependency on outdoor temperature,

B2 = Heating change-point temperature in °F,

C = Baseload in MMBtu,

T = Outdoor temperature in °F, and

$(\ )^{+}$ = Positive values only inside the parenthesis

In a similar fashion to the 3PC change-point linear model of the building, one of the strengths of the 3PH change-point linear model is that the 3PH regression coefficients (i.e., *B1*, *B2* and *C* in equation (4.13)) characterize physical properties of the building envelope and operation of the heating system.

The 3PH coefficient *C* represents weather-independent natural gas use that is used year-round such as hot water heater for shower, laundry, and dishwasher and so on. The 3PH coefficient *B1* represents weather-dependent natural gas use that is used for heating the building. This coefficient is related to heating loads and heating system efficiency of the building so that it can be expressed by equation (4.14). In this equation, since the sum of conductive heat loss through the building envelope and sensible heat lost through air infiltration account for the heating loads of the building, *HC* can be expressed by equation (4.15). Lastly, the 3PH coefficient, *B2* is defined as the outdoor temperature which begins space heating of the building. The *B2* is a function of the heating thermostat set-point temperature; the sum of the internal loads from electricity use, solar heat gain and occupants of the building; and heat transfer coefficient (i.e., *HC* in equation (4.15)) of the building envelope so that it can be expressed by equation (4.16) (Sever et al. 2011).

$$B1 = \frac{HC}{\eta_h} \tag{4.14}$$

$$HC = \left(\frac{A_{roof}}{R_{roof}} + \frac{A_{wall}}{R_{wall}} + \frac{A_{window}}{R_{window}} + \frac{A_{floor}}{R_{floor}}\right) + V \cdot \rho \cdot C_p \tag{4.15}$$

$$B2 = T_{hsp} - \frac{Q_i}{HC} \tag{4.16}$$

Where η_h = Heating system efficiency,

A = Area of heat transfer,

R = Building envelope resistance,

V = Air infiltration rate,

ρ = Air density,

C_p = Air specific heat,

T_{hsp} = Heating thermostat set-point temperature, and

Q_i = Internal loads

As shown from the equations (4.9) through (4.16), the coefficients of the 3PC and the 3PH change-point models vary by the physical properties of the building envelope and operation of the HVAC systems (Sever et al. 2011). Figure 4.12 shows an example of changes to the regression coefficients for the 3PC change-point model due to changes of the each physical property of the building envelope and the HVAC system (i.e., CC, η_c, T_{csp} and Q_i). In Figure 4.12, if the heat transfer of the building envelope (CC) decreases, then the cooling slope and cooling change-point temperature will be decreased, and if the cooling system efficiency (η_c) decreases, the cooling slope will be decreased theoretically. In addition, if the cooling thermostat set-point temperature (T_{csp}) decreases, the cooling change-point temperature will be decreased, and if the internal load (Q_i) decreases, the cooling change-point temperature will be decreased theoretically (Sever et al. 2011).

Considering the theoretical interpretations that the building envelope and operation of the HVAC systems of the building may affect the coefficients of the 3PC and the 3PH change-point models, related simulation input parameters were selected as listed in Table 4.4. For example, for heat transfer of the building envelope, wall R-value, window U-value, roof R-value, wall absorption, roof absorption and infiltration rate were selected as the related simulation parameters. Using the selected simulation parameters, the theoretical interpretations will be demonstrated using building energy simulation in next subsection, and the selected simulation parameters will be used for calibrating the building simulation as key parameters.

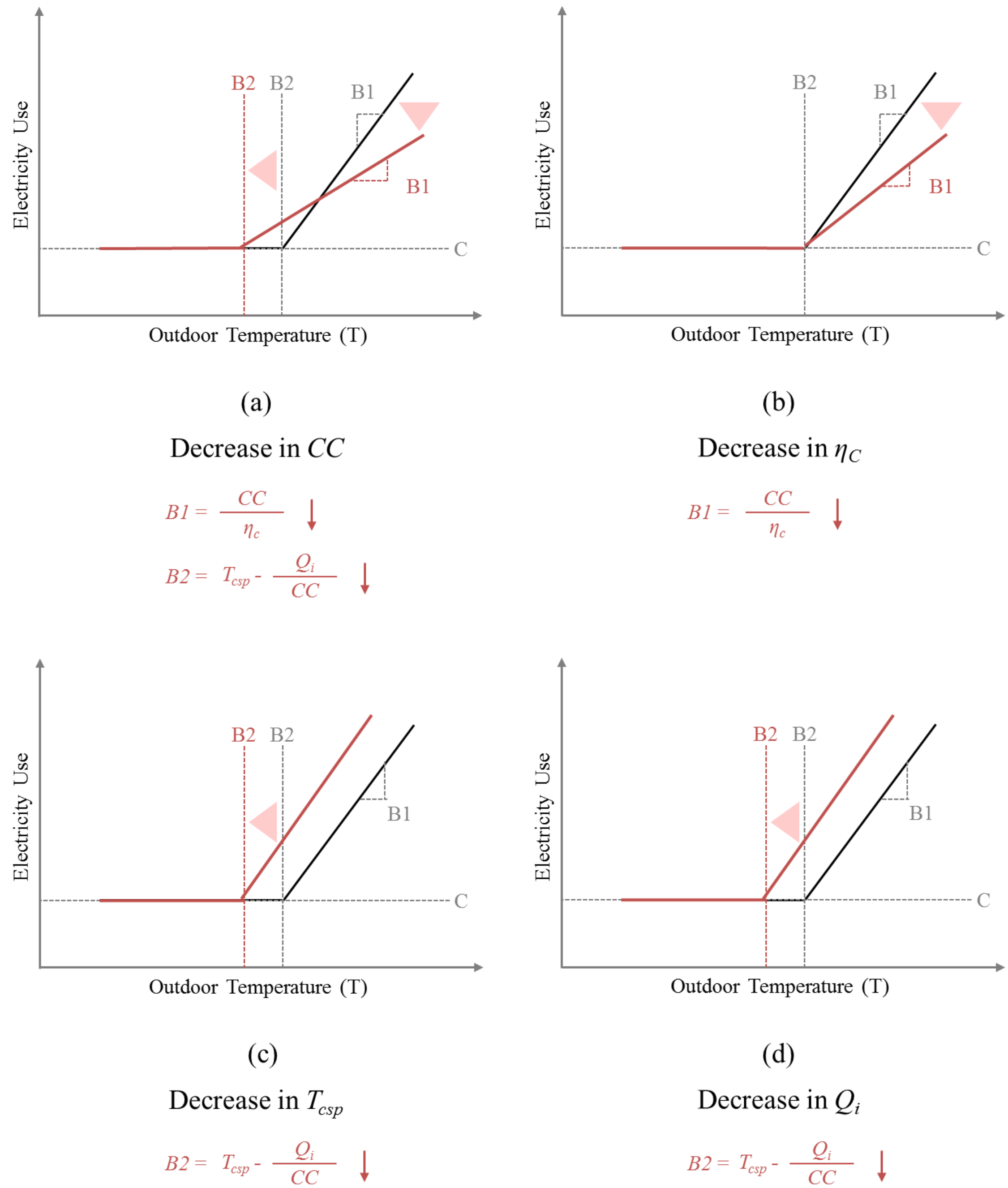


Figure 4.12 The 3PC Model Changes due to: (a) Decrease in CC, (b) Decrease in η_c , (c) Decrease in T_{csp}, and (d) Decrease in Q_i (Reproduced from Sever et al. 2011)

Table 4.4 The Simulation Input Parameters Corresponding to the Coefficients

Coefficients	Electricity Use		Natural Gas Use	
	Related Building Envelope and Systems	Simulation Parameters	Related Building Envelope and Systems	Simulation Parameters
C **Baseload or Weather-independent Loads**	Internal Load	Lightings & Equipment	Hot Water Heater	Hot Water Heater Efficiency (Energy Factor: EF)
B2 **Change-point Temperature**	Thermostat Setpoint Temperature	Cooling Thermostat Setpoint Temperature	Thermostat Setpoint Temperature	Heating Thermostat Setpoint Temperature
	Building Envelope	Shading Devices	Building Envelope	Shading Devices
		Solar Heat Gain Coefficient (SHGC)		Solar Heat Gain Coefficient (SHGC)
		Lightings & Equipment (L&E)		Lightings & Equipment (L&E)
		Window-to-wall Ratio (WWR)		Window-to-wall Ratio (WWR)
B1 **Cooling / Heating Slop or Weather-dependent Loads**	Building Envelope	Wall R-value	Building Envelope	Wall R-value
		Window U-value		Window U-value
		Roof R-value		Roof R-value
		Wall Absorption		Wall Absorption
		Roof Absorption		Roof Absorption
		Infiltration Rate		Infiltration Rate
	System Efficiency	Cooling System Efficiency (Seasonal Energy Efficiency Ratio: SEER)	System Efficiency	Heating System Efficiency (Annual Fuel Utilization Efficiency: AFUE)
		Supply Duct Leakage/R-value		Supply Duct Leakage/R-value
		Return Duct Leakgae/R-value		Return Duct Leakgae/R-value

4.2.2 ASHRAE Inverse Modeling Toolkit (ASHRAE IMT)

To run the ASHRAE Inverse Modeling Toolkit (ASHRAE IMT), the following files first need to be installed in a computer that uses the Microsoft Windows operating systems (Kissock et al. 2002).

- Executable version of toolkit: IMT19.EXE
- Source code version of the toolkit: IMT19.F90
- Example data files: DAILY.DAT, NONUNIPP.DAT
- Example instruction files: DAILY.INS, NONUNIPP.INS
- Required DLL files: SALFLIBC.DLL, FTN90.DLL

Two input files come with the IMT: a data file and an instruction file. The data file contains the required variables that need to be regressed, and the instruction file contains the operating instructions for the IMT so it can identify the data file, find the desired data fields and specific data records in the data file, as well as selecting the appropriate regression model. As shown in the list above, two types of input files are produced with the IMT: the DAILY.DAT and NONUNIPP.DAT are the two data files and the DAILY.INS, NONUNIPP.INS files are the instruction files for the DAILY.DAT and NONUNIPP.DAT data files respectively. The first data file, DAILY.DAT is a uniform time-scale data file that contains daily outdoor temperatures and daily energy use of a building. The DAILY.DAT file can be used to run a mean, two-parameter change-point (2P), three-parameter change-point (3P), four-parameter change-point (4P), five parameter change-point (5P) and Multiple Variable Regression (MVR) models. The second data file, NONUNIPP.DAT is a nonuniform-timescale file that contains monthly energy use and occupancy data, and daily outdoor temperature data in the same file. The NONUNIPP.DAT file format can be used to run mean 2P, 3P, 4P, 5P and MVR models or VBDD models for a building that has monthly energy and daily average use data.

In this study, the NONUNIPP.DAT file format was used for the input data file and NONUNIPP.INS file was used for the instruction file to regress the monthly building electricity use and natural gas use against daily outdoor temperatures. Figure 4.13 shows an example of the NONUNIPP.DAT data file for monthly electricity use for the case-study house. From the first to the ninth column of the fields need to be filled in with month, day, year, monthly electricity use, grouping field ("1" for pre-retrofit period and "2" for post-retrofit period), dummy independent variables 1, 2, 3 and average daily temperature (°F) in order.

Additionally, Figure 4.14 shows an example of the NONUNIPP.INS instruction file for generating 3PC model of electricity use. The instruction file consists of 14 lines of a single field each. Line 1 is for the path and name of the data file and line 2 is the value of the no-data flag. This value indicates missing data in the data file. Typically "-99" is used for the no-data flag but any numeric value can be defined. Line 3 is for the column number of the grouping field in the data file, which defines a column that indicates which records should be included in the regression model. Line 4 indicates a specific record from the column that was defined in line 3 by inputting value "1" of valid grouping field in the data file. The value "1" in the grouping field indicates that this record should be included in the regression model. Line 5 is for residual file. If the value "1" is input in the file, a residual output file IMT.RES will be generated along with the IMT.OUT file. Line 6 is for the selected regression model using the numbers of "1" through "9". The numbers of "1" through "9" indicate each regression model option in order of mean, 2P, 3PC, 3PH, 4P, 5P, MVR, Heating Degree Day (HDD) and Cooling

Degree Day (CDD). Line 7 is for the column number of dependent variable. The number of "4" in Figure 4.14 indicates the records in the fourth column in the data file as a dependent variable that is monthly electricity use in this case. Line 8 is for the number of independent variables. The number of "1" in Figure 4.14 indicates that there is one independent variable used in this model, the average daily temperature in this case. Lines 9 through 14 are for the column number of independent variables in data file. The number of "9" in Figure 4.14 indicates one independent variable is in the ninth column in the data file.

1. MO	2. DAY	3. YR	4. Elec.	5. Pre/Post	6, 7, 8 Dummy Variables			9. OA Temp
1	10	2010	-99	-99	-99	-99	-99	54.7
1	11	2010	788	1	-99	-99	-99	61.5
1	12	2010	-99	-99	-99	-99	-99	70.6
1	13	2010	-99	-99	-99	-99	-99	65.1
1	14	2010	-99	-99	-99	-99	-99	54.5
1	15	2010	-99	-99	-99	-99	-99	58.4
1	16	2010	-99	-99	-99	-99	-99	64.7
1	17	2010	-99	-99	-99	-99	-99	64.0
1	18	2010	-99	-99	-99	-99	-99	67.7
1	19	2010	-99	-99	-99	-99	-99	64.7
1	20	2010	-99	-99	-99	-99	-99	54.3

Figure 4.13 An Example of the NONUNIPP.DAT Data File for the Case-study House

```
Line 1: Path and name of input data file = NONUNIPP.DAT
Line 2: Value of no-data flag = -99
Line 3: Column number of group field = 5
Line 4: Value of valid group field = 1
Line 5: Residual file needed (1 yes, 0 no) = 0
Line 6: Model (1:Mean,2:2p,3:3pc,4:3ph,5:4p,6:5p,7:MVR,8:HDD,9:CDD) = 3
Line 7: Column number of dependent variable Y = 4
Line 8: Number of independent variables (0 to 6)  = 1
Line 9: Column number of independent variable X1 = 9
Line 10: Column number of independent variable X2 = 0
Line 11: Column number of independent variable X3 = 0
Line 12: Column number of independent variable X4 = 0
Line 13: Column number of independent variable X5 = 0
Line 14: Column number of independent variable X6 = 0
```

Figure 4.14 An Example of the NONUNIPP.INS Instruction File for the Case-study House

```
*******************************************************
 ASHRAE INVERSE MODELING TOOLKIT (1.9)
*******************************************************
   Output file name = IMT.out
*******************************************************
   Input data file name =  NONUNIPP.DAT
   Model type =           3P Cooling
   Grouping column No =     5
   Value for grouping =     1
   Residual mode =          0
   # of X(Indep.) Var =     1
   Y1 column number =       4
   X1 column number =    9
   X2 column number =    0 (unused)
   X3 column number =    0 (unused)
   X4 column number =    0 (unused)
   X5 column number =    0 (unused)
   X6 column number =    0 (unused)
*******************************************************
   Regression Results
  --------------------------------------
          N =      12
  --------------------------------------
         R2 =      0.978
  --------------------------------------
      AdjR2 =      0.978
  --------------------------------------
       RMSE =       5.1192
  --------------------------------------
    CV-RMSE =      7.675%
  --------------------------------------
          p =      0.262
  --------------------------------------
         DW =      1.458 (p>0)
  --------------------------------------
         N1 =       4
  --------------------------------------
         N2 =       8
  --------------------------------------
        Ycp =      34.9724 (       2.1005)
  --------------------------------------
         LS =       0.0000 (       0.0000)
  --------------------------------------
         RS =       3.6645 (       0.1724)
  --------------------------------------
        Xcp =      63.3772 (       0.7089)
  --------------------------------------
```

Figure 4.15   An Example of the IMT.OUT File for the Case-study House

When the input files are ready, the IMT can be run by clicking the IMT19.EXE icon and typing the instruction file name, "NONUNIPP.INS" on the automatically opened DOS window. After running the IMT, an output file IMT.OUT will be generated in the same directory as IMT.EXE. The generated output file contains IMT model coefficients, goodness-of-fit parameters, and the information entered in the operating instructions as ASCII text file. Figure 4.15 shows an example of IMT.OUT file.

4.2.3 Application of Three-parameter Change-point Regression Model to the Actual Building Energy Use and the Simulated Building Energy Use using the IMT

The actual building energy use and the simulated building energy use were regressed against the local outdoor temperature by the three-parameter change-point regression model using the IMT as a preliminary step for a sensitivity analysis and semi-automatic calibrated simulation. For the actual building energy use, one year of monthly utility billing data for electricity and natural gas was used, and for the simulated building energy use, the hourly-report from the easy-to-use simulation (DDP) for electricity and natural gas was used. The reason that the monthly utility billing data was used as the measured energy use in this study is that it was easy to obtain and it provided a real example of electricity use and natural gas use for the residential building.

A procedure of the application of the three-parameter change-point regression model to the actual building energy use and the simulated building energy use using the IMT is shown in Figure 4.16, and more details of explanation will be described in next subsections.

4.2.3.1 Application of Three-parameter Change-point Regression Model to the Actual Building Energy Use using the IMT

Annual monthly utility billing data (i.e., twelve-month monthly utility billing data) for electricity use and natural gas use obtained from a homeowner was used as the measured energy use of the building in this study. In order to obtain a three-parameter change-point regression model of the obtained annual monthly utility billing data for electricity use and natural gas use against local outdoor temperature using the IMT, the

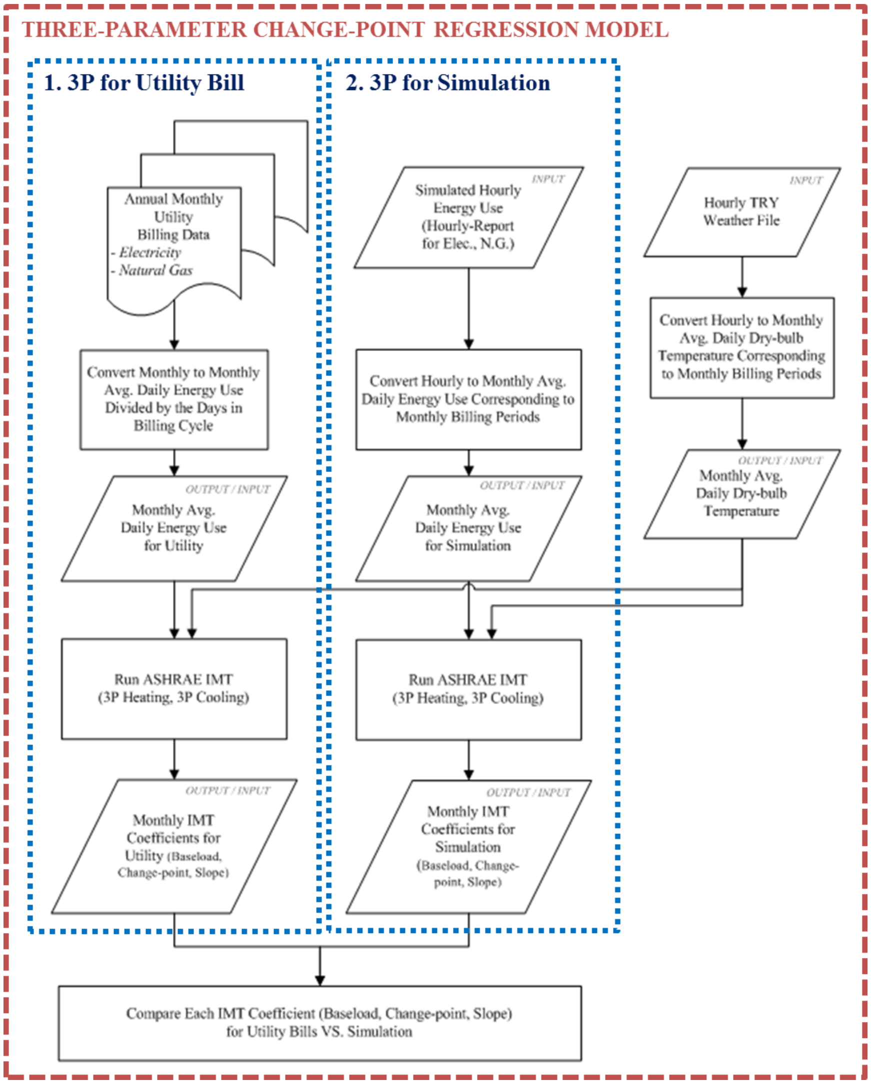


Figure 4.16 Procedure for Three-parameter Change-point Regression Model for the Actual Building Energy Use and the Simulated Building Energy Use

day-adjusted model of three-parameter change-point regression model was applied. Details of the day-adjusted model were explained in the previous section 2.5.2.1.3.

In the first step of the regression process, the monthly utility billing data was converted to monthly average daily electricity use and natural gas use by dividing the monthly amount by the days in the billing cycle. At the same time, the coincident hourly outdoor temperature was also converted to monthly average daily outdoor temperature corresponding to monthly billing periods. Figure 4.17 shows an example of the day-adjusted monthly average daily electricity use, natural gas use and local outdoor temperature. Using the monthly average daily electricity use (46.4 kWh for March) and natural gas use (0.09 MMBtu for March), and monthly average daily outdoor temperature (71.5°F and 70.8°F for electricity and natural gas billing periods respectively), the 3PC model for electricity use and 3PH model for natural gas were regressed against the corresponding local outdoor temperature using the IMT. In such a fashion, the monthly 3P coefficients (i.e., baseload, change-point temperature and slope) for electricity use and natural gas use were obtained as shown in Figure 4.18.

However, the utility billing data may not be used directly for calibrated simulation as an actual energy use of the house since the data may include abnormal energy use that can affect to inaccurate calibration. For example, a long term vacation may be shown as extremely low energy use for a certain month, and therefore this data needs to be adjusted for calibration. In this case, the 3P coefficients obtained from utility billing data of electricity and natural gas uses were used. For example, when the natural gas use is extremely low as shown in Figure 4.19 (a) during the summer, this data should be confirmed by the homeowner whether the homeowner and his/her family were out of home for vacation during the period or not, and if yes, this data should be replaced by appropriate data that is on the regression model as shown in Figure 4.19 (b). The decision for the abnormal energy use data can be conducted by setting upper and lower limits for each coefficient to identify outliers that could be indicating abnormal energy use data. The upper and lower limits are determined by CV (RMSE) of regression models shown in Figure 4.18, and in Figure 4.19 as the dotted lines.

4.2.3.2 Application of Three-parameter Change-point Regression Model to the Simulated Building Energy Use using the IMT

The hourly-reports for electricity use and natural gas use were obtained from the output file of the easy-to-use simulation that uses the DOE-2.1e program. Figure 4.20 shows an example of the hourly-report output files of the easy-to-use simulation. In order to obtain a three-parameter, change-point regression model of the annual, simulated energy use for electricity use and natural gas use against the local outdoor temperature using the IMT, the day-adjusted model of three-parameter change-point regression model was applied in a similar fashion to the monthly utility billing data.

To begin, the simulated hourly energy use was converted to monthly average daily electricity use and natural gas use divided by the days in the month. At the same time, local hourly outdoor temperature from the simulation's weather file was also converted to monthly average daily outdoor temperature corresponding to each month. Using the converted monthly average daily electricity use and natural gas use, and monthly average daily outdoor temperature, a 3PC model for the simulated electricity use and 3PH model for the simulated natural gas were regressed against the corresponding local outdoor temperature using the IMT to determine the coefficients for the simulated electricity and natural gas use (i.e., baseload, change-point temperature and slope).

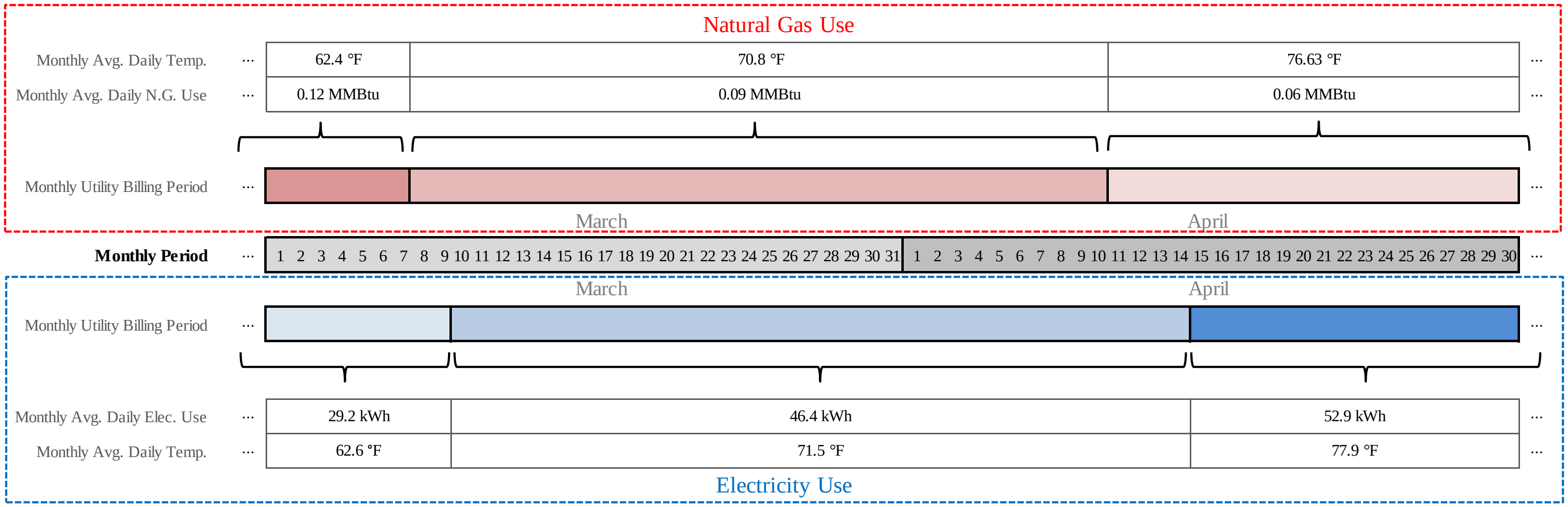


Figure 4.17 An Example of the Day-adjusted Monthly Average Daily Electricity Use (March 10th to April 14th), Natural Gas Use (March 8th to April 10th) and Local Outdoor Temperature

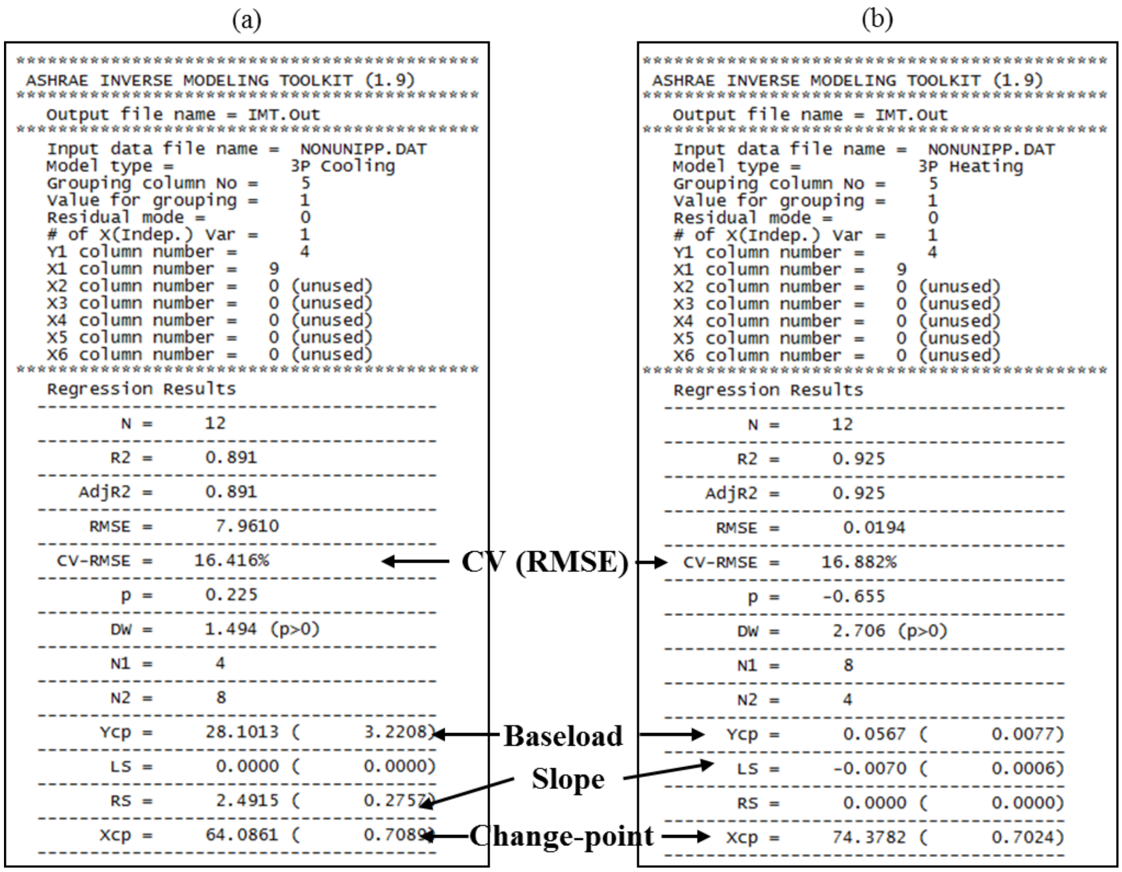
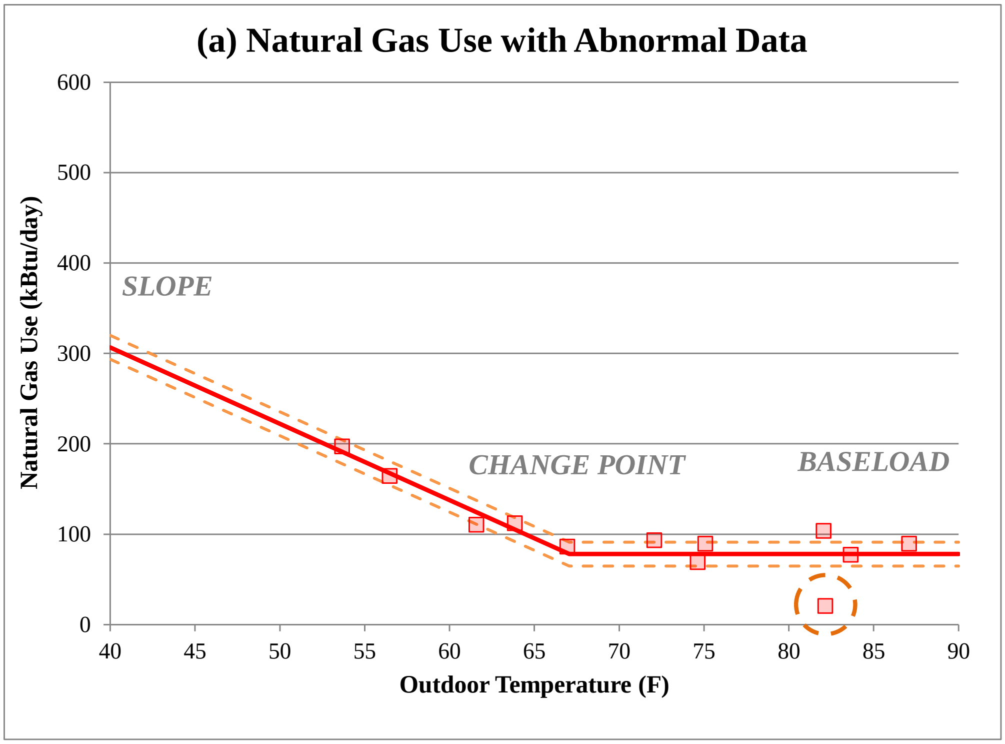


Figure 4.18 An Example of the 3P Coefficients for Actual Building Energy Use of: (a) Electricity Use and (b) Natural Gas Use



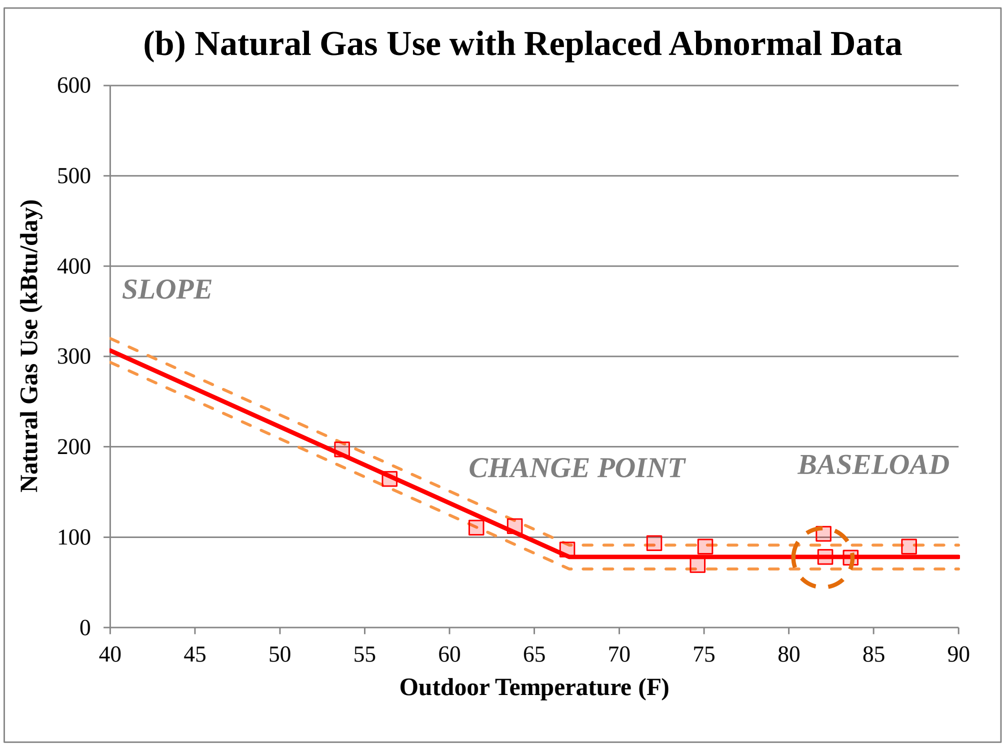


Figure 4.19 An Example of an abnormal 3P Coefficient of: (a) Natural Gas Use and (b) Replaced Electricity Use by 3PH Baseload Coefficient

(a)

```
REP1                  = HOURLY-REPORT
-------------------------------------
             PLANT

             TOTAL
             ELECTRIC
             KW

             ----(10)
 8 1 1              2.514
 8 1 2              2.145
 8 1 3              2.049
 8 1 4              2.148
 8 1 5              1.898
 8 1 6              1.804
 8 1 7              2.260
 8 1 8              3.154
 8 1 9              4.168
 8 110              4.463
 8 111              5.213
 8 112              6.217
 8 113              6.423
 8 114              7.434
 8 115              7.680
 8 116              7.346
 8 117              7.301
 8 118              6.762
 8 119              4.916
 8 120              3.944
 8 121              3.187
 8 122              3.308
 8 123              3.274
 8 124              3.070
0 DAILY SUMMARY (AUG  1)
    MN              1.804
    MX              7.680
    SM            102.678
    AV              4.278
```

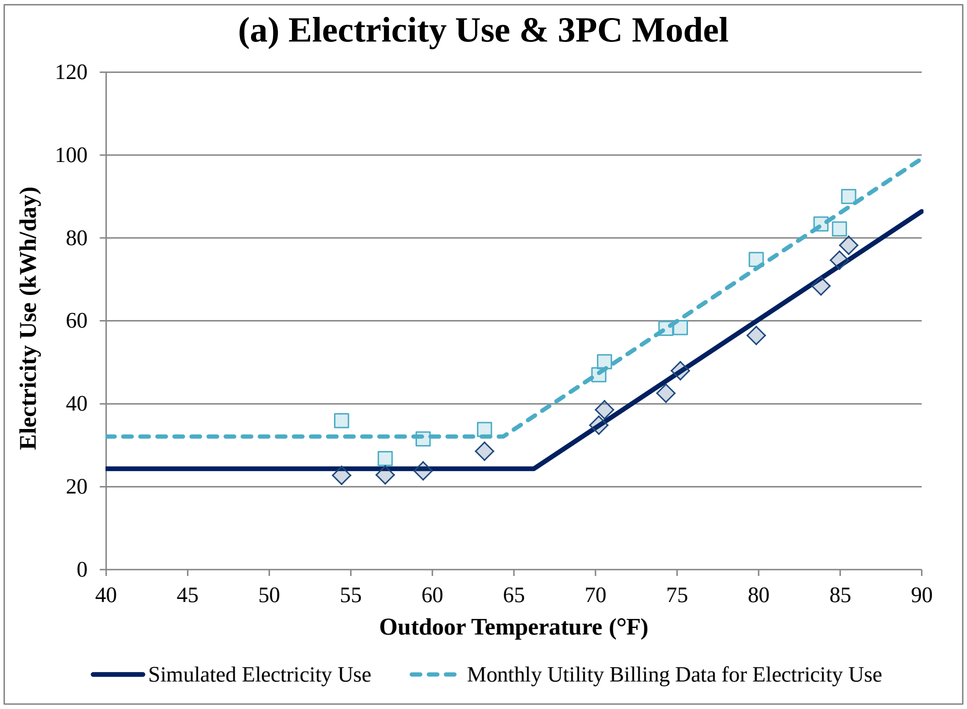
(b)

```
REP1                  = HOURLY-REPORT
------------------------------------------------------
MMDDHH  GLOBAL         END-USE          END-USE

        DRY BULB       HEATING          DHW HEAT
        TEMP           FUEL PA1         FUEL PA1
        F              BTU/HR           BTU/HR

        ----( 8)       ----(15)         ----(18)
 1 1 1      56.0         2482.826         3292.188
 1 1 2      56.0         5696.542         3292.188
 1 1 3      57.0         5200.066         3292.188
 1 1 4      61.0         4895.679         3292.188
 1 1 5      62.0         4651.885         3292.188
 1 1 6      63.0         4460.800         3292.188
 1 1 7      63.0         4650.091         3292.188
 1 1 8      63.0         4376.991         3292.188
 1 1 9      64.0            0.000         3292.188
 1 110      66.0            0.000         3292.188
 1 111      68.0            0.000         3292.188
 1 112      69.0            0.000         3292.188
 1 113      72.0            0.000         3292.188
 1 114      73.0            0.000         3292.188
 1 115      73.0            0.000         3292.188
 1 116      72.0            0.000         3292.188
 1 117      72.0            0.000         3292.188
 1 118      70.0            0.000         3292.188
 1 119      70.0            0.000         3292.188
 1 120      69.0            0.000         3292.188
 1 121      69.0            0.000         3292.188
 1 122      63.0            0.000         3292.188
 1 123      61.0            0.000         3292.188
 1 124      62.0            0.000         3292.188
0 DAILY SUMMARY (JAN  1)
    MN      56.0            0.000         3292.188
    MX      73.0         5696.542         3292.188
    SM    1574.0        36414.879        79012.508
    AV      65.6         1517.287         3292.188
```

Figure 4.20 An Example of Desktop DOE-2 Processor (DDP) Hourly-Report for: (a) Electricity Use and (b) Natural Gas Use

4.2.3.3 Comparison of Three-parameter Change-point Regression Model between the Actual Building Energy Use and the Simulated Building Energy Use

The day-adjusted electricity and natural gas use from the actual building energy use and the simulated building energy use were then plotted as shown in Figure 4.21. Figure 4.21shows the comparison plots of the day-adjusted monthly average daily electricity and natural gas use for the actual building energy use and the simulated building energy use. In addition, the 3PC coefficients for electricity use and 3PH



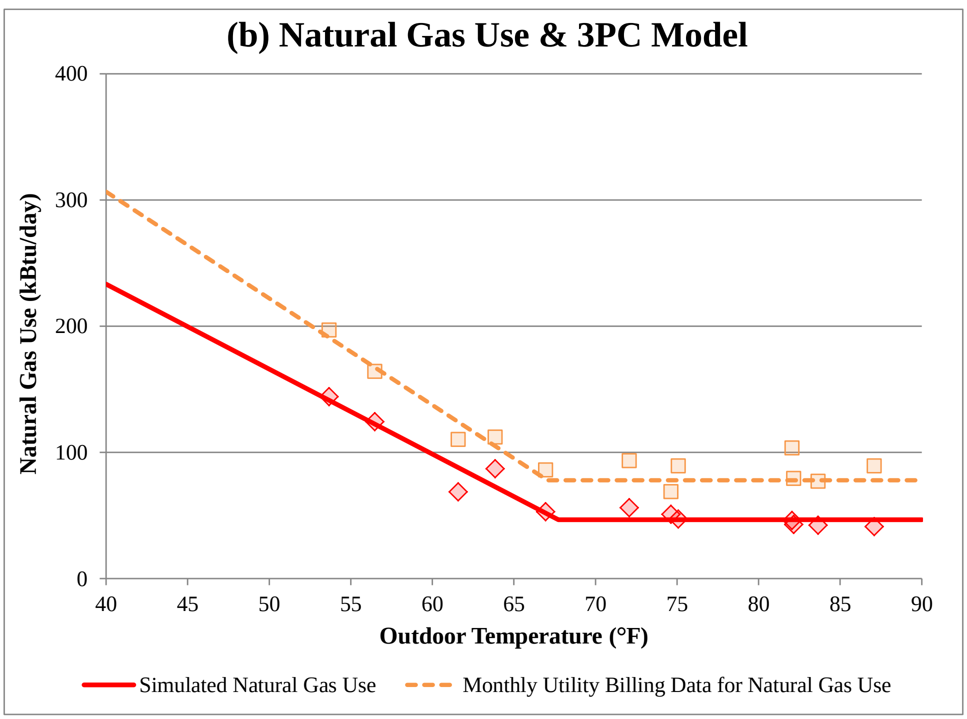


Figure 4.21 Comparison Plots of: (a) Electricity Use & 3PC Models and (b) Natural Gas Use & 3PH Models between the Actual Building Energy Use and the Simulated Building Energy Use

coefficients for natural gas use from the actual building energy use and the simulated building energy use were also plotted as shown.

4.2.4 Sensitivity Analysis using Three-parameter Change-point Regression Model

Next, a sensitivity analysis of the simulated input parameters was performed using the IMT three-parameter change-point regression model to identify the most influential simulation input parameters which could be used for calibration of the building simulation. The overall procedure of a sensitivity analysis is shown in Figure 4.22.

4.2.4.1 Comparison of Simulation Input Parameters

In order to identify the sensitivity of the simulation input parameters, 20 simulation parameters were selected for analysis in this study. For the 20 simulation inputs, the previous literature concerning calibrated simulation, including Alspector (2008), Cho and Haberl (2008), Haberl and Bou-Saada (1998), Liu et al. (2003) and Manke and Hittle (1996) was reviewed. Once the 20 parameters were selected, a characteristic analysis was performed with the 3PC and 3PH coefficients as described in previous Section 4.2.1. In addition, selected parameters were excluded from the analysis, including architectural parameters such as house size, shape, and orientation of the house.

The sensitivity analysis of the selected simulation parameters was performed by changing the parameter values one at a time from 50% to 150% of their nominal values (i.e., obtained from the case-study house owner), in increments of 10% while holding the other parameters constant. Table 4.5 shows each run of the simulation with its nominal

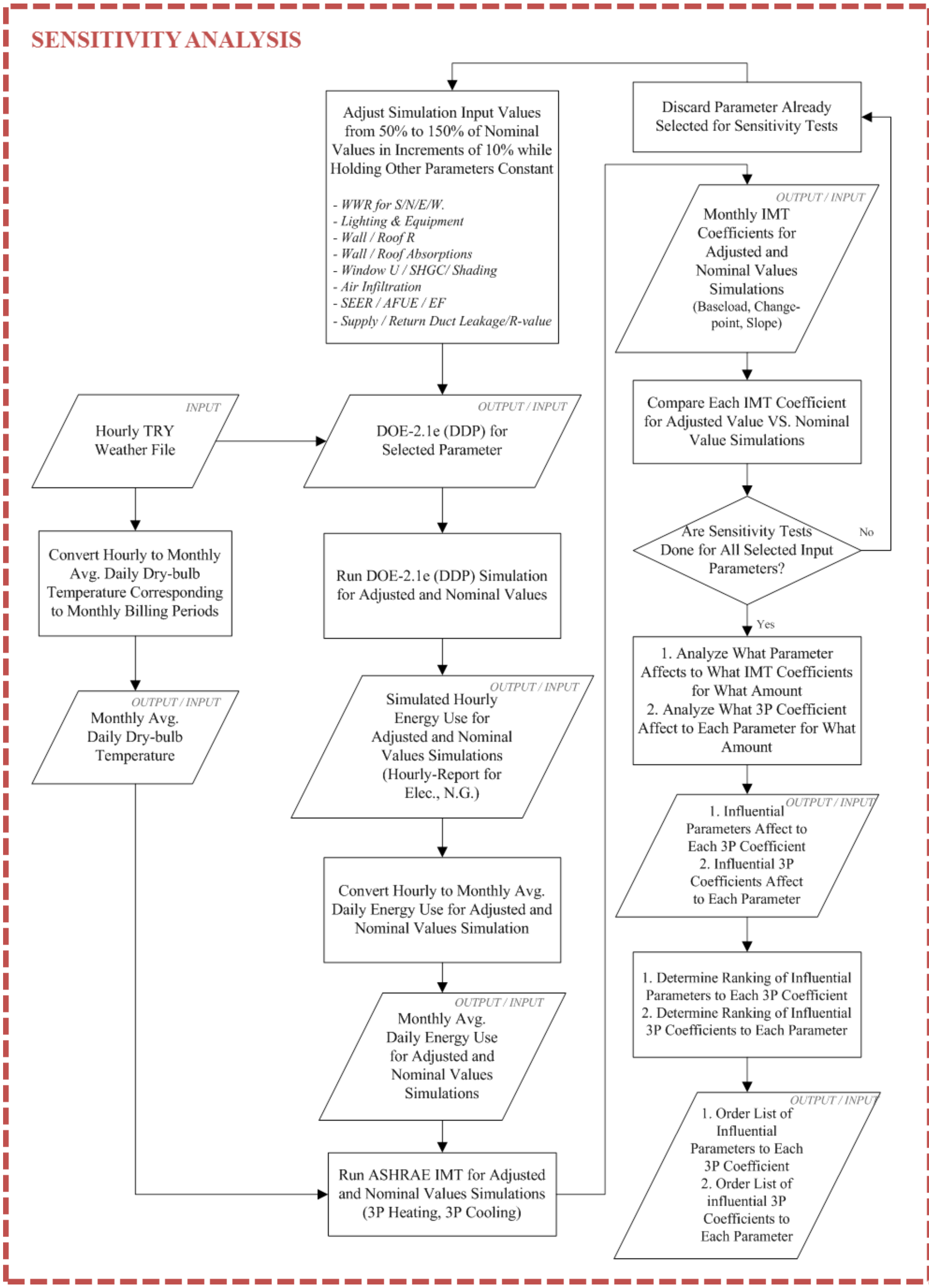


Figure 4.22 Procedure for a Sensitivity Analysis

value and varied range of values used in this analysis. Each run in Table 4.5 was run with the DDP using an hourly TRY file with coincident weather data. Simulated electricity use and natural gas use were then extracted from the hourly-report for each case run. The simulation results were then regressed against the coincident outdoor temperature using the three-parameter change-point regression models of the IMT. Each 3PC and 3PH coefficient for each run was then calculated using the procedure explained in Section 4.2.3. These simulations were run for all 20 selected simulation parameters. Figure 4.23 shows an example of plots for selected parameter runs.

4.2.4.2 Ranking of the Influential Simulation Parameters for Each 3P Coefficient

The next step was to identify which parameters affected each 3P coefficient. In order to do this, the 3P coefficients from the simulation runs of the sensitivity tests for each parameter were first calculated under varying conditions. Table 4.6 shows an example how a 3P coefficient changes when the wall R-value varies from 6.5 hr-ft^2-°F/Btu to 19.5 hr-ft^2-°F /Btu. Table 4.7 shows the percentage difference from the nominal values of each coefficient for the wall R-values.

Next, the percentage range of each coefficient for the wall R-value shown at the 7th column in Table 4.7 was calculated using equation (4.17). This procedure was then repeated for all 20 simulation parameters. The results are summarized in Table 4.8. The 2nd column in Table 4.8 shows the variations range from 50% to 150% of the 3P change-point coefficient for the 20 simulation parameters. The 3rd column shows the percentage change of 20 simulation parameters for 3P change-point coefficients. The ranking of the influential simulation input parameters for each 3P coefficient will be further discussed in Chapter 5 (i.e., Section 5.1.3. Sensitivity Analysis Results for Case-study House #1).

$$\%\ Range\ from\ Nominal\ Value = \frac{Maximum\ Value - Minimum\ Value}{Nominal\ Value} \tag{4.17}$$

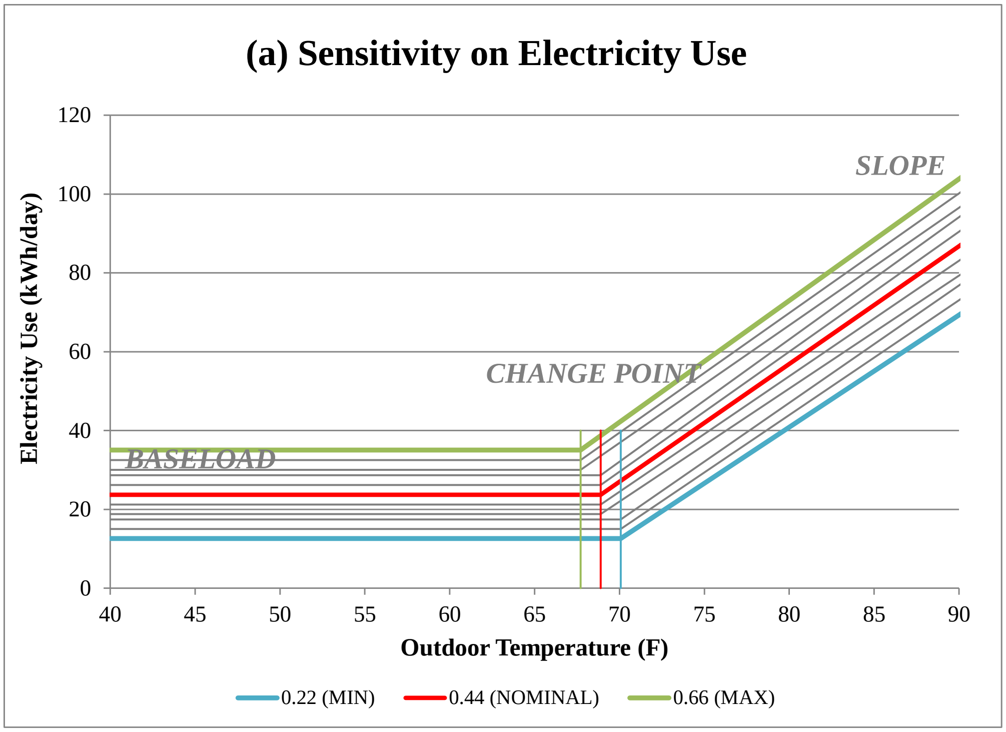
4.2.4.3 Ranking of the Influential 3P Coefficients for Each Simulation Input Parameter

The next step was to identify which 3P coefficient was the most influential for each simulation parameter. The last column in Table 4.7 shows the percentage of each coefficient for each parameter. This can be calculated by equation (4.18). In this case, the 3PH slope was the most influential coefficient for the wall R-value changes with a 53.4% change. The results of the other parameters will be discussed in Chapter 5 (5.1.3. Sensitivity Analysis Results for Case-study House #1).

$$\%\ of\ Coefficient\ for\ Each\ Parameter = \frac{Each\ \%\ Range\ from\ Nominal\ Value\ for\ Selected\ Parameter}{Sum\ \ of\ \%\ Range\ from\ Nominal\ Value\ for\ Selected\ Parameter} \tag{4.18}$$

Table 4.5 Sensitivity Analysis Table for the Selected 20 Simulation Input Parameters

Input	Building Envelope												System							
	Wall R-value	Window U-value	Roof R-value	Wall Absorption	Roof Absorption	Shading Devices	Solar Heat Gain Coefficient (SHGC)	Infiltration Rate	WWR South	WWR East	WWR West	WWR North	Lighting & Equipment	Cooling System Efficiency (SEER)	Heating System Efficiency (AFUE)	Hot Water Heater Efficiency (EF)	Supply Duct Leakage	Return Duct Leakage	Supply Duct R-value	Return Duct R-value
1	6.5 - 19.5	0.87	29.6	0.55	0.75	4	0.66	0.57	18.8	18.8	18.8	18.8	0.44	10	0.66	0.53	0.1	0.1	8	4
2	13	0.44 - 1.31	29.6	0.55	0.75	4	0.66	0.57	18.8	18.8	18.8	18.8	0.44	10	0.66	0.53	0.1	0.1	8	4
3	13	0.87	14.8 - 44.4	0.55	0.75	4	0.66	0.57	18.8	18.8	18.8	18.8	0.44	10	0.66	0.53	0.1	0.1	8	4
4	13	0.87	29.6	0.28 - 0.83	0.75	4	0.66	0.57	18.8	18.8	18.8	18.8	0.44	10	0.66	0.53	0.1	0.1	8	4
5	13	0.87	29.6	0.55	0.075 - 0.975	4	0.66	0.57	18.8	18.8	18.8	18.8	0.44	10	0.66	0.53	0.1	0.1	8	4
6	13	0.87	29.6	0.55	0.75	2 - 6	0.66	0.57	18.8	18.8	18.8	18.8	0.44	10	0.66	0.53	0.1	0.1	8	4
7	13	0.87	29.6	0.55	0.75	4	0.33 - 0.99	0.57	18.8	18.8	18.8	18.8	0.44	10	0.66	0.53	0.1	0.1	8	4
8	13	0.87	29.6	0.55	0.75	4	0.66	0.29 - 0.86	18.8	18.8	18.8	18.8	0.44	10	0.66	0.53	0.1	0.1	8	4
9	13	0.87	29.6	0.55	0.75	4	0.66	0.57	9.4 - 28.2	18.8	18.8	18.8	0.44	10	0.66	0.53	0.1	0.1	8	4
10	13	0.87	29.6	0.55	0.75	4	0.66	0.57	18.8	9.4 - 28.2	18.8	18.8	0.44	10	0.66	0.53	0.1	0.1	8	4
11	13	0.87	29.6	0.55	0.75	4	0.66	0.57	18.8	18.8	9.4 - 28.2	18.8	0.44	10	0.66	0.53	0.1	0.1	8	4
12	13	0.87	29.6	0.55	0.75	4	0.66	0.57	18.8	18.8	18.8	9.4 - 28.2	0.44	10	0.66	0.53	0.1	0.1	8	4
13	13	0.87	29.6	0.55	0.75	4	0.66	0.57	18.8	18.8	18.8	18.8	0.22 - 0.66	10	0.66	0.53	0.1	0.1	8	4
14	13	0.87	29.6	0.55	0.75	4	0.66	0.57	18.8	18.8	18.8	18.8	0.44	5 - 15	0.66	0.53	0.1	0.1	8	4
15	13	0.87	29.6	0.55	0.75	4	0.66	0.57	18.8	18.8	18.8	18.8	0.44	10	0.33 - 0.99	0.53	0.1	0.1	8	4
16	13	0.87	29.6	0.55	0.75	4	0.66	0.57	18.8	18.8	18.8	18.8	0.44	10	0.66	0.26 - 0.79	0.1	0.1	8	4
17	13	0.87	29.6	0.55	0.75	4	0.66	0.57	18.8	18.8	18.8	18.8	0.44	10	0.66	0.53	0.05 - 0.15	0.1	8	4
18	13	0.87	29.6	0.55	0.75	4	0.66	0.57	18.8	18.8	18.8	18.8	0.44	10	0.66	0.53	0.1	0.05 - 0.15	8	4
19	13	0.87	29.6	0.55	0.75	4	0.66	0.57	18.8	18.8	18.8	18.8	0.44	10	0.66	0.53	0.1	0.1	4 - 12	4
20	13	0.87	29.6	0.55	0.75	4	0.66	0.57	18.8	18.8	18.8	18.8	0.44	10	0.66	0.53	0.1	0.1	8	2 - 6



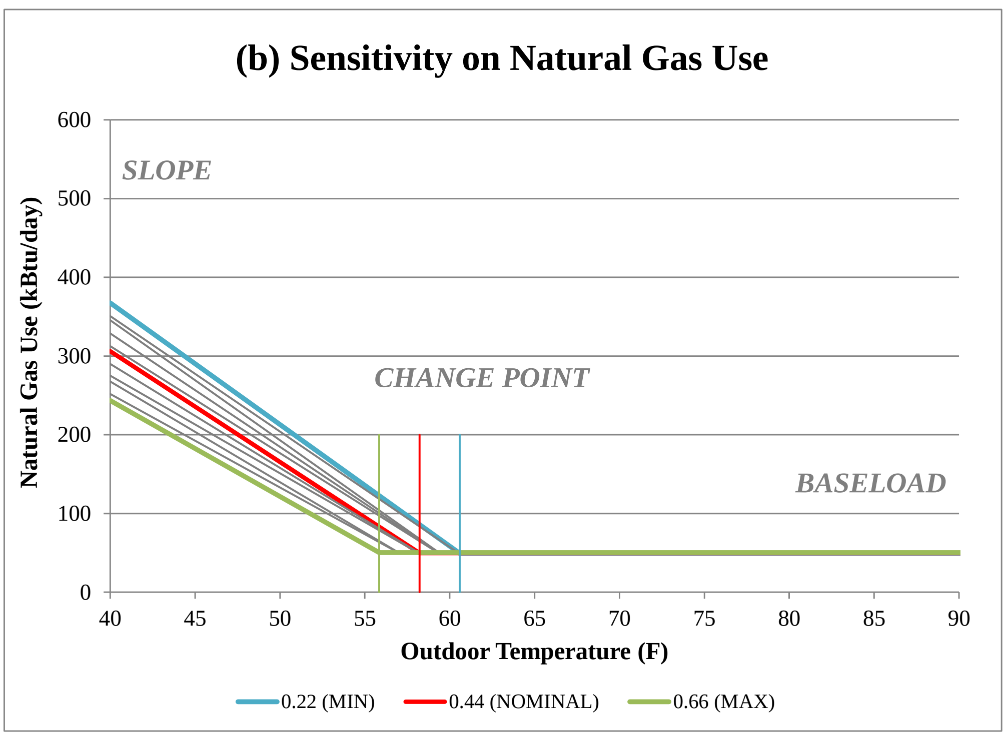


Figure 4.23 An Example of Sensitivity Results for: (a) Electricity Use and (b) Natural Gas Use of a Selected Simulation Input Parameter

Table 4.6 An Example of 3P Coefficient Changes by Wall R-value Changes

Electricity Use (3PC)

		Change Point (F)	**Baseload (kWh)**	**Slope (kWh/F)**
Wall R-value	6.5 (MIN)	68.89	23.46	3.09
	7.8	68.89	23.52	3.06
	9.1	68.89	23.58	3.04
	10.4	68.89	23.62	3.02
	11.7	68.89	23.66	3.00
	13.0 (NOMINAL)	68.89	23.69	2.99
	14.3	68.89	23.72	2.98
	15.6	68.89	23.74	2.97
	16.9	68.89	23.76	2.96
	18.2	68.89	23.78	2.95
	19.5 (MAX)	68.89	23.79	2.94

Natural Gas Use (3PH)

		Change Point (F)	**Baseload (kWh)**	**Slope (kWh/F)**
Wall R-value	6.5 (MIN)	59.41	48.66	-14.82
	7.8	59.41	48.57	-14.23
	9.1	58.22	50.03	-15.14
	10.4	58.22	49.92	-14.72
	11.7	58.22	49.82	-14.37
	13.0 (NOMINAL)	58.22	49.74	-14.06
	14.3	58.22	49.68	-13.82
	15.6	58.22	49.63	-13.60
	16.9	58.22	49.59	-13.41
	18.2	58.22	49.55	-13.25
	19.5 (MAX)	58.22	49.51	-13.11

Table 4.7 An Example of Percentage Difference from Nominal Values of 3P Coefficients for Wall R-value

Sensitivity Analysis Parameters	3P Coefficients		Minimum (50%)	Maximum (150%)	Nominal	% of Range from Nominal Value [%]	% of Coefficient for Each Parameter [%]
Wall R-value	**Elec.**	**Change Point (F)**	68.89	68.89	68.89	0.0%	0.0%
		Base Load (kWh)	23.46	23.79	23.69	1.4%	6.1%
		Slope (kWh/F)	3.09	2.94	2.99	5.0%	22.0%
	N.G.	**Change Point (F)**	59.41	58.22	58.22	2.0%	8.9%
		Base Load (kBtu)	48.66	49.51	49.74	2.2%	9.5%
		Slope (kBtu/F)	-14.82	-13.11	-14.06	12.2%	53.4%

Table 4.8 Share of the Percentage of the Simulation Parameters for Each 3P Coefficient

	Electricity Use					
	Change Point [F]		**Base Load [kWh]**		**Slope [kWh/F]**	
	% Diff	**% of Change Point**	**% Diff**	**% of Base Load**	**% Diff**	**% of Slope**
Wall R-value	0.00%	0.00%	1.40%	0.87%	5.02%	1.72%
Window U-value	1.72%	20.00%	5.01%	3.12%	14.32%	4.91%
Roof R-value	0.00%	0.00%	2.33%	1.45%	14.77%	5.06%
Wall Absorption	0.00%	0.00%	3.78%	2.35%	6.66%	2.28%
Roof Absorption	0.00%	0.00%	4.92%	3.06%	19.83%	6.80%
Shading Devices	0.00%	0.00%	11.22%	6.98%	8.69%	2.98%
SHGC	3.44%	40.00%	9.24%	5.74%	4.22%	1.45%
Infiltration Rate	0.00%	0.00%	2.17%	1.35%	8.67%	2.97%
L&E	3.44%	40.00%	94.83%	58.98%	7.98%	2.74%
SEER	0.00%	0.00%	10.13%	6.30%	119.23%	40.86%
AFUE	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
EF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Supply Duct Leakage	0.00%	0.00%	1.20%	0.75%	10.03%	3.44%
Return Duct Leakage	0.00%	0.00%	2.19%	1.36%	27.21%	9.32%
Supply Duct R-value	0.00%	0.00%	0.05%	0.03%	15.41%	5.28%
Return Duct R-value	0.00%	0.00%	0.14%	0.09%	3.07%	1.05%
WWR South	0.00%	0.00%	5.80%	3.60%	4.52%	1.55%
WWR East	0.00%	0.00%	4.00%	2.49%	6.86%	2.35%
WWR West	0.00%	0.00%	1.08%	0.67%	6.89%	2.36%
WWR North	0.00%	0.00%	1.30%	0.81%	8.43%	2.89%
TOTAL	8.61%	100%	160.79%	100%	291.82%	100%

Table 4.8 Continued

	Natural Gas Use					
	Change Point [F]		Base Load [kBtu]		Slope [kBtu/F]	
	% Diff	% of Change Point	% Diff	% of Base Load	% Diff	% of Slope
Wall R-value	2.04%	9.09%	2.17%	1.42%	12.2%	2.7%
Window U-value	4.07%	18.18%	0.54%	0.35%	66.6%	14.9%
Roof R-value	2.04%	9.09%	0.87%	0.56%	30.5%	6.8%
Wall Absorption	0.00%	0.00%	1.13%	0.73%	10.3%	2.3%
Roof Absorption	0.00%	0.00%	0.38%	0.25%	7.1%	1.6%
Shading Devices	0.00%	0.00%	0.66%	0.43%	19.0%	4.2%
SHGC	2.04%	9.09%	1.31%	0.85%	27.9%	6.2%
Infiltration Rate	0.00%	0.00%	1.45%	0.95%	41.0%	9.1%
L&E	8.15%	36.36%	2.02%	1.32%	23.2%	5.2%
SEER	0.00%	0.00%	0.01%	0.01%	1.0%	0.2%
AFUE	2.04%	9.09%	1.99%	1.29%	131.4%	29.3%
EF	2.04%	9.09%	137.06%	89.25%	2.8%	0.6%
Supply Duct Leakage	0.00%	0.00%	0.10%	0.06%	9.6%	2.2%
Return Duct Leakage	0.00%	0.00%	0.37%	0.24%	9.4%	2.1%
Supply Duct R-value	0.00%	0.00%	0.30%	0.20%	11.4%	2.6%
Return Duct R-value	0.00%	0.00%	0.07%	0.05%	1.8%	0.4%
WWR South	0.00%	0.00%	0.25%	0.16%	4.6%	1.0%
WWR East	0.00%	0.00%	0.75%	0.49%	7.3%	1.6%
WWR West	0.00%	0.00%	1.03%	0.67%	15.2%	3.4%
WWR North	0.00%	0.00%	1.10%	0.72%	15.7%	3.5%
TOTAL	22.41%	100%	153.57%	100%	448.10%	100%

4.2.5 Calibrated Simulation

The easy-to-use simulation that uses the statistical house information database was calibrated using annual monthly utility billing data of electricity and natural gas uses. To select the parameters for calibrating the simulation, all the parameters used for the sensitivity tests were analyzed, and the most influential to the least influential parameters for each 3P coefficient were identified (described in Section 4.2.4.2). After that, each parameter beginning from the most influential to the least influential applied to the calibration. For example, if the parameters, L&E (58.98%), shading devices (6.98%) , SEER (6.30%), SHGC (5.74%), WWR for south (3.60%), window U-value (3.12%), roof absorption (3.06%), WWR for east (2.49%) represented the most influential to the least influential parameters in order for the 3PC baseload coefficient as shown in Table 4.8, these parameters become candidates for calibrated simulation for adjusting the 3PC baseload. This rule was applied for the other 3P coefficients as well.

However, not all the candidate parameters chosen for each 3P coefficient were used for the calibration; some of them were eliminated dropped out. The reason for this is better explained with the following example: as shown in Table 4.8, the parameter, *shading devices* was one of the influential parameters for 3PC baseload, but it was also influential parameters for 3PC slope and 3PH slope coefficients. In this case, another result of the sensitivity analysis that showed the most influential 3P coefficients for each simulation parameter (described in Section 4.2.4.3) was used. For example, if the parameter, *shading devices* was the most influential parameter affecting to 3PH slope, the *shading devices* would be used for calibration to adjust 3PH slope rather than other coefficients (i.e., 3PC baseload and slope). In this way, the process for the other parameters continued, and the parameters as well as the order that the parameters need to be calibrated for adjusting selected 3P coefficients were decided. The results are listed in Chapter 5 (5.1.3 Sensitivity Analysis Result for Case-study House #1).

Following this, the calibrated simulation was begun using the parameters that corresponded to the 3PC baseload coefficient, and continued to the other parameters that correspond to 3PH baseload, 3PC change-point temperature, 3PH change-point temperature, 3PC slope and 3PH slope in order for adjusting the corresponding 3P coefficients to match the actual energy use.

There was one exception in which the parameters not used in the sensitivity analysis were used for the calibration. These were the cooling and heating thermostat set-point temperature parameters. To adjust the 3P change-point temperature coefficients, the cooling and heating thermostat set-point temperature parameters were used for the calibration based upon the characteristics of 3P model as shown in equations (4.12) and (4.16). The reason for this order was to adjust the weather-independent (i.e., 3P baseload coefficients) parameters first, and followed by the weather-dependent (i.e., 3P change-point temperature and slope coefficients) parameters.

The overall procedure for the calibrated simulation is as following: First, the parameter for calibration was varied from approximately 50% to 150% of their nominal values, in 2% increments, while the other parameters were held constant[5]. For an indicator to find the best fit of a parameter, the global CV (RMSE) which includes

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[5] However, the variations and increments were slightly different depending upon the parameters.

electricity CV (RMSE) and natural gas CV (RMSE) was used. These were calculated by comparing the energy use obtained by the simulation model versus the utility billing data. The equations for electricity CV (RMSE), natural gas CV (RMSE) and global CV (RMSE) are shown in equations (4.19), (4.20) and (4.21), respectively. Second, after finding the parameter value that produced the minimum global CV (RMSE) through the simulations, the next parameters were chosen and the same procedure was used to find the minimum global CV (RMSE), while holding the parameter value that was already decided from the previous step. This procedure for calibration was carried out for all 22 parameters, including the cooling and heating thermostat set-point temperature parameters until reaching equal or less than the required accuracy criterion, which was 15% of monthly global CV (RMSE). This tolerance value was chosen based on the ASHRAE Guideline 14-2002 recommendation (ASHRAE 2002). In this way, the simulation model was calibrated using all the parameter values that were determined by adjusting each parameter until the minimum global CV (RMSE) was obtained.

In addition, along with the calibration of the easy-to-use simulation, the as-built simulation was also calibrated through the same procedure to verify that the easy-to-use simulation had been calibrated appropriately. The comparison of these two calibrated simulation will be presented in Chapter 5 (Section 5.1.6).

$$CV\ (RMSE)_{Electricity} = \frac{\sqrt{\frac{\sum_{i=1}^{n}(y_{simulated,i} - y_{data,i})^2}{n-1}}}{\bar{y}_{data}} \times 100 \tag{4.19}$$

$$CV\ (RMSE)_{Natural\ Gas} = \frac{\sqrt{\frac{\sum_{i=1}^{n}(y_{simulated,i} - y_{data,i})^2}{n-1}}}{\bar{y}_{data}} \times 100 \tag{4.20}$$

$$CV\ (RMSE)_{Global} = \frac{\sqrt{\frac{\sum_{i=1}^{n}(y_{simulated,i} - y_{data,i})^2}{n-1}}}{\bar{y}_{data}} \times 100 \tag{4.21}$$

Where $y_{simulated,i}$ = A simulated dependent variable value corresponding to a particular set of values of the independent variables,

$y_{data,i}$ = The data value of the dependent variable for the same set of independent variables above,

$\bar{y}_{data}$ = The mean value of the dependent variable of the data set,

n = number of data points in the data set.

4.3 Development of a Methodology for Determination of the Potential Energy Conservation Measures

In this study, a methodology for determining the potential energy conservation measures (ECMs) is proposed. Figure 4.24 shows the flow of the determination procedure of the ECMs. This section can be divided into two phases: 1) a standard house compliant with the 2009 International Energy Conservation Code (IECC), and 2) the determination of the potential ECMs, which includes a calculation of annual energy savings and pay-back period of the potential ECMs. Details for these will be explained in following subsections.

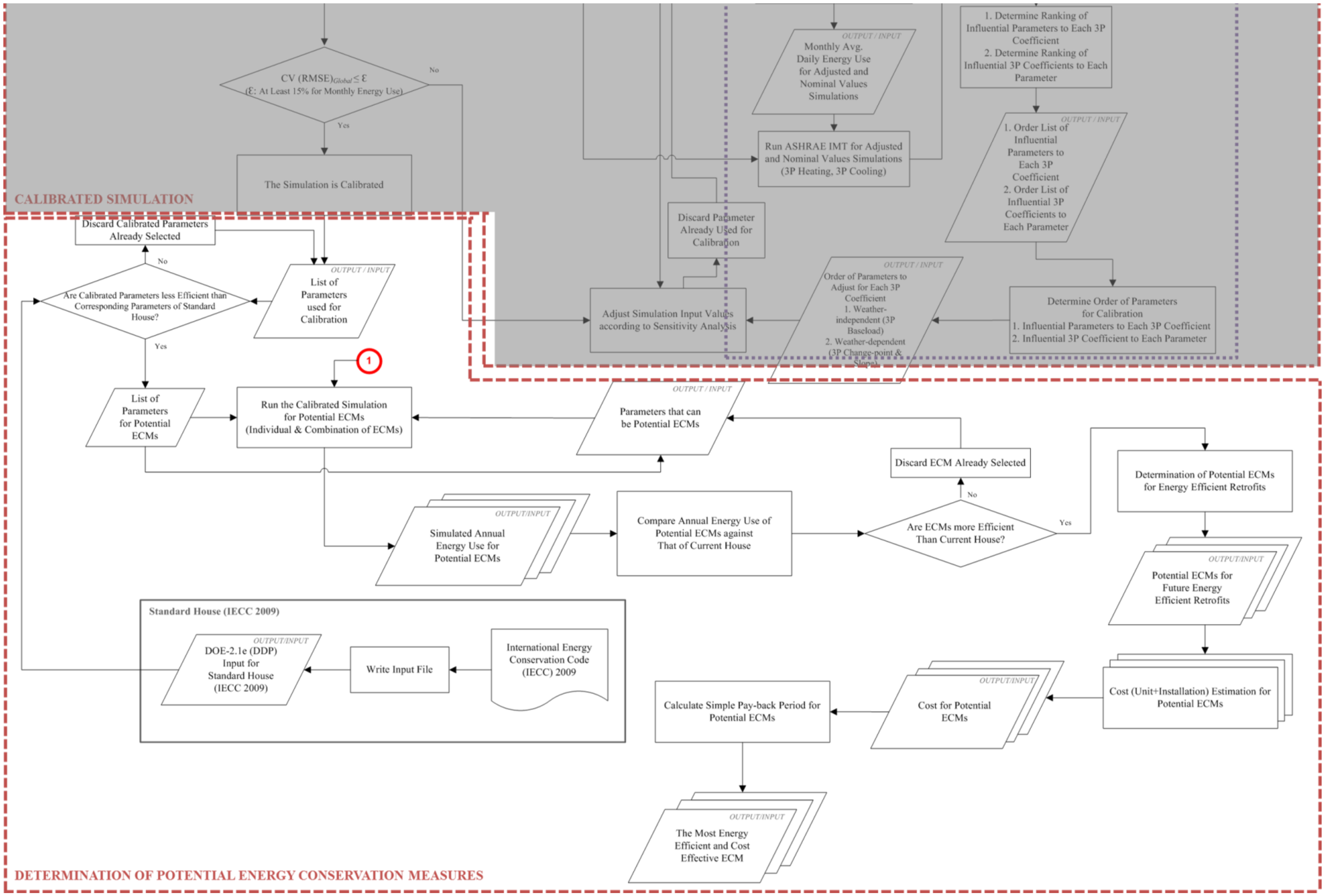


Figure 4.24 Procedure for Determination of the Potential Energy Conservation Measures

4.3.1 A Standard House Compliant with the 2009 IECC

In order to model a standard house that is compliant with the 2009 IECC using the DDP, the performance path alternative provided in the 2009 IECC was used. Since the case-study houses are located in College Station and Plano, Texas, which belong to the Climate Zone 2 and 3 respectively, the corresponding 2009 IECC simulation parameters were used.

The standard house is a single-family house with space conditioning systems that use electricity for space cooling, natural gas for space heating and domestic hot water heating. The ducts are located in the attic, and the specifications for the duct leakage and the duct R-value were assumed to be compliant with the 2009 IECC. Detailed specifications for the building envelope and systems are listed in Table 4.9 for the Climate Zone 2 and Table 4.10 for the Climate Zone 3.

4.3.2. Determination of the Potential Energy Conservation Measures

For the determination of the potential ECMs of the house, the calibrated simulation parameters and the corresponding standard house parameters that are compliant with the 2009 IECC were compared. The calibrated simulation parameter values which are much less energy efficient than the corresponding parameter values of the standard house were used as the potential ECMs. For case-study house #1 two calibrated simulation parameters (i.e., the easy-to-use simulation and the as-built simulation) were compared to the standard house parameters. The result of the comparison will be presented in Chapter 5 (Section 5.1.9).

Table 4.9 Simulation Parameters for a Standard House in the Climate Zone 2

Component			**Standard House (CZ 2)**
Envelope	Window to Floor Ratio (%)		15
	Exterior Wall	Absorptance (fraction)	0.75
		Average Wall Height (ft.)	8
		Overall U-value (Btu/hr-ft^2-°F)	0.082
		Frame Fraction (%)	25
	Window	Frame Type	Vinyl
		U-value (Btu/hr-ft^2-°F)	0.65
		SHGC (fraction)	0.3
	Roof / Attic	Roof Emissivity (fraction)	0.9
		Absorptance (fraction)	0.75
		Attic Type	Full Attic
		Gross Area (ft^2)	2,391
		Ceiling R-value (Hr-ft^2-°F/Btu)	27.8
	Slab-on-grade Floor	Gross Area (ft^2)	2,391
		Slab R-value (Hr-ft2-°F/Btu)	0
Infiltration		Infiltration Rate (ACH)	0.35
Systems	Heating System	Fuel	Natural Gas
		System Type	Furnace
		Efficiency (AFUE)	78
		Capacity (kBtu/hr)	60
		System Location	Attic
	Cooling System	System Type	Air Conditioner, Air Cooled
		Efficiency (SEER)	13
		Capacity (kBtu/hr)	60
		System Location	Attic
	Domestic Hot Water	Fuel	Natural Gas
		Capacity (Gallon)	40
		Energy Factor (EF)	0.59
		Temperature Settings (°F)	120
	Ducts	Supply R-value (Hr-ft2-°F/Btu)	6
		Return R-value (Hr-ft2-°F/Btu)	6
		Duct Location	Attic
	Temperatures	Cooling (°F)	75
		Heating (°F)	72
	Lighting & Equipments	Schedule	Constant
		Lighting (kW)	0.47
		Equipment (kW)	0.63

Table 4.10 Simulation Parameters for a Standard House in the Climate Zone 3

Component			Standard House (CZ 3)
Envelope	Window to Floor Ratio (%)		15
	Exterior Wall	Absorptance (fraction)	0.75
		Average Wall Height (ft.)	8
		Overall U-value (Btu/hr-ft^2-°F)	0.082
		Frame Fraction (%)	25
	Window	Frame Type	Vinyl
		U-value (Btu/hr-ft^2-°F)	0.5
		SHGC (fraction)	0.3
	Roof / Attic	Roof Emissivity (fraction)	0.9
		Absorptance (fraction)	0.75
		Attic Type	Full Attic
		Gross Area (ft^2)	2,391
		Ceiling R-value (Hr-ft^2-°F/Btu)	27.8
	Slab-on-grade Floor	Gross Area (ft^2)	2,391
		Slab R-value (Hr-ft2-°F/Btu)	0
Infiltration		Infiltration Rate (ACH)	0.35
Systems	Heating System	Fuel	Natural Gas
		System Type	Furnace
		Efficiency (AFUE)	78
		Capacity (kBtu/hr)	60
		System Location	Attic
	Cooling System	System Type	Air Conditioner, Air Cooled
		Efficiency (SEER)	13
		Capacity (kBtu/hr)	60
		System Location	Attic
	Domestic Hot Water	Fuel	Natural Gas
		Capacity (Gallon)	40
		Energy Factor (EF)	0.59
		Temperature Settings (°F)	120
	Ducts	Supply R-value (Hr-ft2-°F/Btu)	6
		Return R-value (Hr-ft2-°F/Btu)	6
		Duct Location	Attic
	Temperatures	Cooling (°F)	75
		Heating (°F)	72
	Lighting & Equipments	Schedule	Constant
		Lighting (kW)	0.47
		Equipment (kW)	0.63

In addition, a simple calculation of annual energy saving and the corresponding pay-back period of the potential ECMs was performed in this study. First of all, the calibrated simulation house was simulated using the values for each potential ECM and the coincident TRY weather file, and the results compared to the utility billing data. Then annual energy savings were calculated by subtracting the annual site energy use of the case-study house that applied the potential ECM from the annual energy use in utility. Annual energy saving from individual ECM and combination of ECMs were carried out as well. The combination of ECMs was grouped by their characteristics that include the building envelope and fenestration measures, HVAC system measures, and combinations of all measures. The result of the annual energy savings for individual and combination of measures will be shown in Chapter 5 (Section 5.1.8, 5.2.2 and 5.3.2).

After the calculation of the annual site energy savings from the potential ECMs, a simple pay-back period was estimated. In order to do this, the corresponding price for the potential ECM, including the unit and installation costs, was determined. Next, the pay-back period was estimated using the following equation (4.22). In this calculation, the price for natural gas and electricity were assumed to be \$12.77/MMBtu and \$0.117/kWh, respectively, according to the 2012 U.S. Energy Information Administration.

$$Pay - back\ Period = \frac{Estimated\ Retrofit\ Cost\ (Unit + Installation)}{Annual\ Energy\ Saving} \tag{4.22}$$

4.4 Summary of the Methodology

A methodology to develop an accurate, consistent and easy-to-use, semi-automated home energy audit procedure for improvements in energy efficiency in an existing single-family house in a hot and humid climate has been described in this chapter. In order to accomplish this, three methodologies were developed:

1) a methodology that uses an easy-to-use residential simulation for a user who is not familiar with building energy simulation and HVAC systems or other residential systems; 2) a methodology that enables a semi-automatic, calibrated simulation using monthly utility bills for more accurate predictions of energy-efficient retrofits of a house; 3) a methodology for determining the potential savings from energy conservation measures using the calibrated simulation. The results of the application of the methodology described in this chapter will be discussed in the following Chapter 5.

CHAPTER V

RESULTS

This chapter presents the results of the easy-to-use simulations, calibrated simulations, and the determination of the potential energy conservation measures (ECMs) for three case-study houses located in College Station and Plano, Texas, along with the results of the sensitivity analysis that was used for the calibration. In addition, the results of the calibration and the determination of the potential ECM using easy-to-use simulation was compared with those using the as-built simulation to verify that the easy-to-use simulation had been worked appropriately. Details of the results will be presented in the corresponding subsections in this chapter.

5.1 Description of Case-study House #1

The case-study house #1 is a single-family house located in College Station, Texas. The required building characteristics and photos were obtained from the homeowner through the survey sheet. Figure 5.1 through Figure 5.4 show the appearance of the case-study house #1 taken from different points of view, and Table 5.1 shows a summary of the building characteristics (Im 2003). The annual monthly utility bills for the electricity and natural gas use during 2012 were also obtained from the homeowner. Table 5.2 and Table 5.3 show the monthly electricity and natural gas utility billing data, and calculated monthly average daily use, respectively. In addition, the approval for this case-study house from the Institutional Review Board (IRB) for the research compliance and biosafety’s human subject’s protection program was attached in Figure A.1 in Appendix A.

For the case-study house #1, two types of simulations were performed, which were an as-built simulation that uses the building characteristics shown in Table 5.1, and an easy-to-use simulation that uses only a minimum number of input parameters and statistical building information from the created house information database. The as-built simulation and the easy-to-use simulation results were compared, and the calibration results for both simulations were compared as well in the following subsections.

Figure 5.1 Front View (Southeast) of the Case-study House #1

Figure 5.2 Back View (Northwest) of the Case-study House #1

Figure 5.3 Side View (Southwest) of the Case-study House #1

Figure 5.4 Side View (Northeast) of the Case-study House #1

Table 5.1 Building Characteristics of the Case-study House #1

Component			Case-study House #1
Envelope	Window to Wall Ratio		18.8%
	Exterior Wall	Wall Color	Dark
		Gross Area	1,564 ft^2
		Average Wall Height	8 ft
		Insulation R Value	R-13
		Stud Spacing	16"
	Windows	Gross Area	295 ft^2
		Glazing Type	Clear Double Pane
		Frame Type	Aluminum
		U Value	0.87
		SHGC	0.66
	Roof / Attic	Roof Color	Dark
		Ceiling Type	Ceiling with Attic Above
		Gross Area	2,391 ft^2
		Insulation R Value	R-29.6 (8" insulation Depth)
	Slab Floor	Gross Area	2,391 ft^2
		Slab Perimeter R Value	R-0
Infiltration		ACH	N/A
Equipments	Heating System	Fuel	Natural Gas
		System Type	Furnace
		Efficiency (AFUE or HSPF)	66%
		Manufacturer	Lennox
		System Location	Attic
	Cooling System	System Type	Air Conditioner, Air Cooled
		Efficiency (SEER)	10 (9.9 - 10.7)
		Manufacturer	Lennox
		System Location	Unconditioned Area
	Domestic Water Heater	NAECA-covered Water Heating Equipment (yes, no)	Yes
		Fuel	Gas
		Capacity	50 Gallon
		Energy Factor	
		Type	Storage
		Tank Location	Unconditioned Area
		Manufacturer	Rheem

Table 5.2 Monthly Electricity Utility Billing Data for the Case-study House #1

Billing Period		Days in Billing Periods	Monthly Electricity Use (kWh)	Calculated Monthly Avg. Daily Elec. Use (kWh/Day)
Start Date	**End Date**			
12/9/2011	1/10/2012	33	1184	35.9
1/11/2012	2/8/2012	29	776	26.8
2/9/2012	3/8/2012	29	914	31.5
3/9/2012	4/10/2012	33	1551	47.0
4/11/2012	5/8/2012	28	1628	58.1
5/9/2012	6/11/2012	34	2543	74.8
6/12/2012	7/11/2012	30	2501	83.4
7/12/2012	8/9/2012	29	2610	90.0
8/10/2012	9/11/2012	33	2712	82.2
9/12/2012	10/9/2012	28	1634	58.4
10/10/2012	11/7/2012	29	1453	50.1
11/8/2012	12/7/2012	30	1014	33.8

Table 5.3 Monthly Natural Gas Utility Billing Data for the Case-study House #1

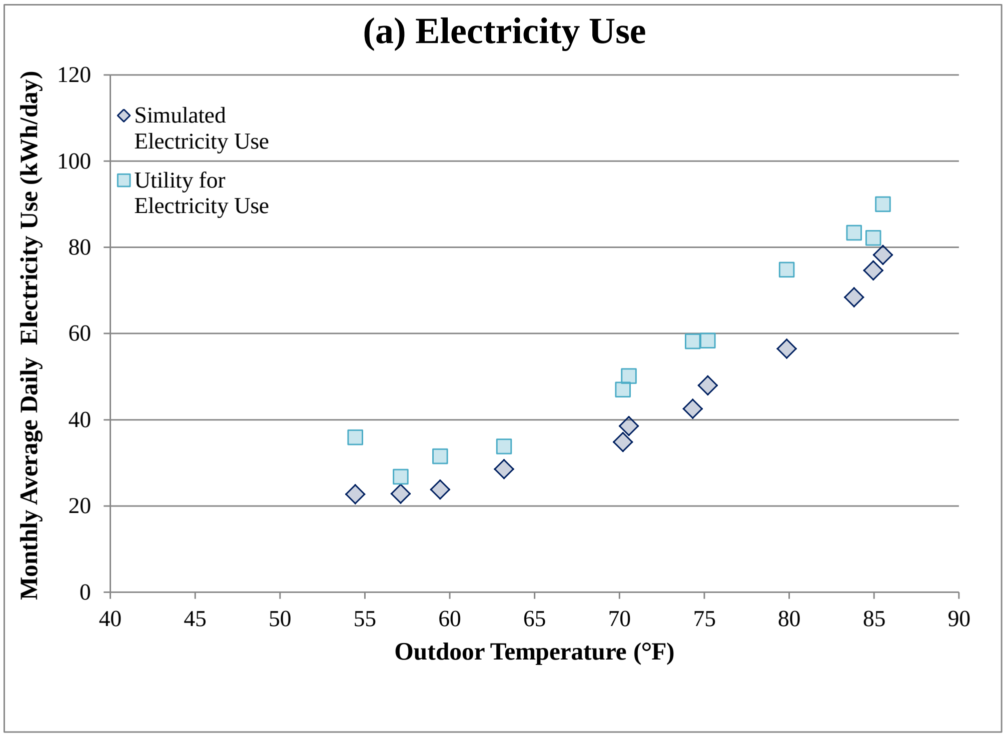
Billing Period		Days in Billing Periods	Monthly N.G. Use (MCF)	Monthly N.G. Use (MMBtu)	Calculated Monthly Avg. Daily N.G. Use (MMBtu/Day)
Start Date	**End Date**				
12/17/2011	1/18/2012	33	6.5	6.5	0.197
1/19/2012	2/15/2012	28	4.6	4.6	0.164
2/16/2012	3/19/2012	33	3.7	3.7	0.112
3/20/2012	4/18/2012	30	2.8	2.8	0.093
4/19/2012	5/17/2012	29	2	2	0.069
5/18/2012	6/14/2012	28	2.9	2.9	0.104
6/15/2012	7/19/2012	35	2.7	2.7	0.077
7/20/2012	8/16/2012	28	2.5	2.5	0.089
8/17/2012	9/19/2012	34	0.7	0.7	0.021
9/20/2012	10/17/2012	28	2.5	2.5	0.089
10/18/2012	11/15/2012	29	2.5	2.5	0.086
11/16/2012	12/14/2012	29	3.2	3.2	0.110

5.1.1 As-built Simulation of Case-study House #1

The as-built simulation was developed using the ESL's DDP software based on the building characteristics information shown in Table 5.1. In the simulation, the occupancy, lighting and equipment, and HVAC operating schedules were set to run 24 hours per a day for a year, and the building geometry was simplified to a square for use with the DDP. The as-built simulation was run with the TRY format weather file for College Station, Texas (Figure D.1 and D.2 in Appendix D), and the hourly and average daily electricity and natural gas use was extracted from the hourly-report of the simulation output file. Figure 5.5 shows the monthly average daily simulated and measured electricity and natural gas use against outdoor temperature. Figure 5.6 also shows the monthly average daily simulated and measured electricity and natural gas use versus outdoor temperature and their 3PC and 3PH regression models from the IMT. As described in Chapter 4, a monthly CV (RMSE) for the as-built simulation was calculated to assess the goodness-of-fit, which yielded 27.3% for the electricity use, 61.6 % for the natural gas use and 36.9% for global, respectively.

5.1.2 Easy-to-use Simulation of Case-study House #1

In a similar fashion as the as-built simulation, the easy-to-use simulation was also developed using the DDP based on the house information database shown in Table 4.3. The case-study house #1 was built in 1990. The corresponding simulation input values of building envelope and HVAC systems were used from the database. In the simulation, the occupancy, lighting and equipment, and HVAC operating schedules were set to run



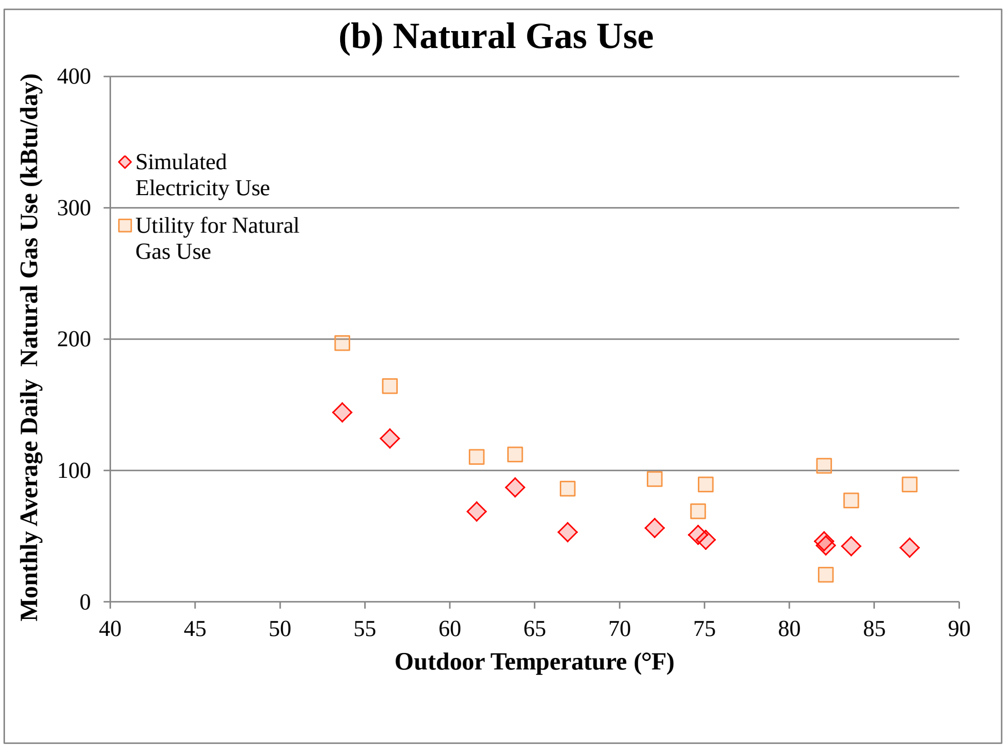


Figure 5.5 Results for the As-built House #1 Simulation and the Monthly Utility Bills for: (a) Electricity Use and (b) Natural Gas Use

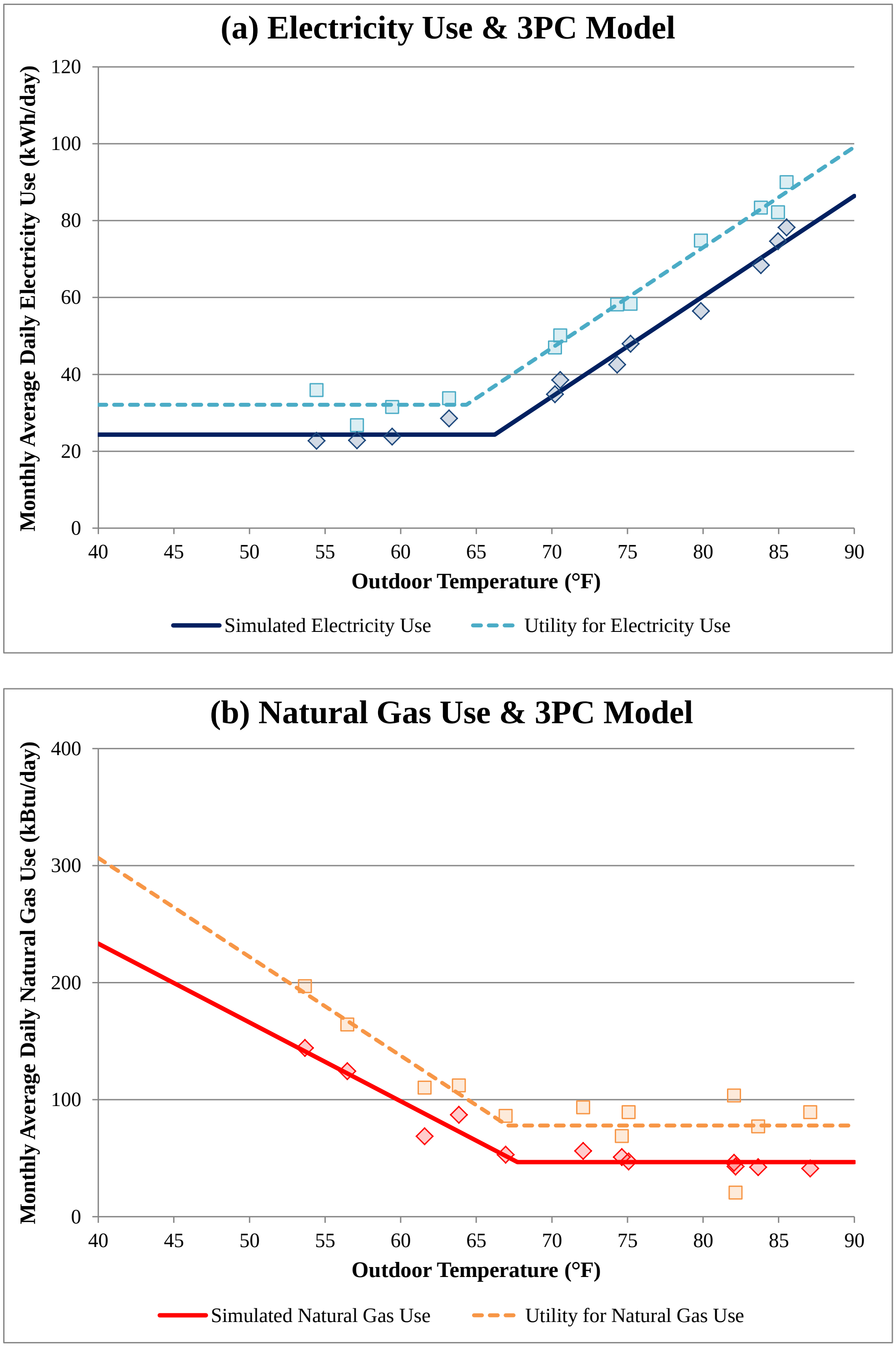


Figure 5.6 *Results for the As-built House #1 Simulation and Monthly Utility Bills, and Corresponding 3P Regression Models for: (a) Electricity Use and (b) Natural Gas Use*

24 hours per a day for a year, and the building geometry was simplified to a square using the DDP in similar way as the as-built simulation. The easy-to-use simulation was run with the TRY format weather file containing College Station, Texas hourly data, and the hourly and average daily electricity and natural gas uses were extracted from the hourly-report from the simulation output. Figure 5.7 shows the monthly average daily plots for the simulated and measured electricity and natural gas uses against outdoor temperature. Figure 5.8 shows the same data as Figure 5.7 along with the 3PC and 3PH regression models calculated with the IMT. The monthly CV (RMSE) for the easy-to-use simulation was calculated to assess the goodness-of-fit, and they were 18.6% for the electricity use, 44.5% for the natural gas use and 26.1% for global, respectively.

5.1.3 Sensitivity Analysis Results for Case-study House #1

A sensitivity analysis for 20 selected simulation parameters was conducted using the three-parameter change-point regression model to identify the most influential simulation parameters to be used for the calibration of the building simulation. Details of the methodology were explained previously in Chapter 4.2.4. The sensitivity test results for the 20 simulation parameters are presented in Figure 5.9 through Figure 5.28. Figure 5.9 (a) presents the effect of the wall R-value [hr-ft^2-°F/Btu] on electricity use varied from 6.5 hr-ft^2-°F/Btu to 19.5 hr-ft^2-°F/Btu, and Figure 5.9 (b) presents the effect of the wall R-value on the natural gas use when the wall R-value was varied from 6.5 hr-ft^2-°F/Btu to 19.5 hr-ft^2-°F/Btu. These plots visually show how the wall R-value changes affect the 3PC and 3PH coefficients. In a similar fashion to Figure 5.9, the sensitivity test results for window U-value [Btu/hr-ft^2-°F], roof R-value [hr-ft^2-°F/Btu], wall absorption [Fraction], roof absorption [Fraction], shading devices [ft], SHGC [fraction], infiltration rate [ACH], lighting & equipment (L&E) [kW],seasonal energy efficiency ratio (SEER), annual fuel utilization efficiency (AFUE), energy factor (EF), supply duct leakage [Fraction], return duct leakage [Fraction], supply duct R-value [hr-ft^2-°F/Btu], return duct R-value [hr-ft^2-°F/Btu], Window-to-wall ratio (WWR) [%] for south, east, west, and north are shown in Figure 5.10 through Figure 5.24, respectively.

The following observations were obtained from the sensitivity tests:

In Figure 5.9, the wall R-value change has no influence on the 3PC change-point, whereas the wall R-value increases 0.3 kWh of the 3PC baseload, and reduces by 0.2 kWh/°F of the 3PC slope as the wall R-value increases. In addition, the wall R-value reduces by 1.2 °F of the 3PH change-point and 1.7 kBtu/°F of the 3PH slope, and increases 0.8 kBtu of the 3PH baseload and as the wall R-value increases.

In Figure 5.10, the window U-value increases 1.2 °F of the 3PC change-point and 0.4 kWh/°F of the 3PC slope, and reduces by 1.2 kWh of the 3PC baseload as the window U-value increases. In addition, the window U-value increases 2.4 °F of the 3PH change-point and 9.4 kBtu/°F of the 3PH slope, and reduces by 0.1 kBtu of the 3PH baseload as the window U-value increases.

In Figure 5.11, the roof R-value change has no influence on 3PC change-point, whereas the roof R-value reduces by 0.6 kWh of the 3PC baseload and 0.4 kWh/°F of the 3PC slope as the roof R-value increases. In addition, the roof R-value reduces by 1.2 °F of the 3PH change-point, 0.4 kBtu of the 3PH baseload and 4.3 kBtu/°F of the 3PH slope as the roof R-value increases.

In Figure 5.12, the wall absorption change has no influence on the 3PC change-point, whereas the wall absorption increases 0.9 kWh of the 3PC baseload and 0.2kWh/°F of the 3PC slope as the wall absorption increases. In addition, the wall absorption change has no influence on the 3PH change-point, whereas the wall absorption reduces by 0.6 kBtu of the 3PH baseload and 1.4 kBtu/°F of the 3PH slope as the wall absorption increases.

In Figure 5.13, the roof absorption change has no influence on the 3PC change-point, whereas the roof absorption increases 1.1 kWh of the 3PC baseload and 0.6 kWh/°F of the 3PC slope as the roof absorption increases. In addition, the roof absorption change has no influence on the 3PH change-point, whereas the roof absorption reduces by 0.2 kBtu of the 3PH baseload and 1.0 kBtu/°F of the 3PH slope as the roof absorption increases.

In Figure 5.14, the length change of the shading devices has no influence on 3PC change-point, whereas the length of the shading devices reduces by 2.7 kWh of the 3PC baseload and 0.3 kWh/°F of the 3PC slope as the length of the shading devices increases. In addition, the length change of the shading devices has no influence on the 3PH change-point, whereas the length of the shading devices increases 0.3 kBtu of the 3PH baseload and 2.7 kBtu/°F of the 3PH slope as the length of the shading devices increases.

In Figure 5.15, the SHGC reduces by 2.4 °F of the 3PC change-point, and increases 2.2 kWh of the 3PC baseload and 0.1 kWh/°F of the 3PC slope as the SGHC increases. In addition, the SHGC reduces by 1.2 °F of the 3PH change-point and 3.9

kBtu/°F of the 3PH slope, and increases 0.2 kBtu of the 3PH baseload as the SHGC increases.

In Figure 5.16, the infiltration rate change has no influence on the 3PC change-point, whereas the infiltration rate reduces by 0.5 kWh of the 3PC baseload, and increases 0.3 kWh/°F of the 3PC slope as the infiltration rate increases. In addition, the infiltration rate change has no influence on 3PH change-point, whereas the infiltration rate increases 0.7 kBtu of the 3PH baseload and 5.8 kBtu/°F of the 3PH slope as the infiltration rate increases.

In Figure 5.17, the L&E reduces by 2.4 °F of the 3PC change-point, and increases 22.5 kWh of the 3PC baseload and 0.2 kWh/°F of the 3PC slope as the L&E increases. In addition, the L&E reduces by 4.7 °F of the 3PH change-point and 3.3 kBtu/°F of the 3PH slope, and increases 1.0 kBtu of the 3PH baseload as the L&E increases.

In Figure 5.18, the SEER change has no influence on the 3PC change-point, whereas the SEER reduces by 2.4 kWh of the 3PC baseload and 3.6 kWh/°F of the 3PC slope as the SEER increases. In addition, the SEER change has no influence on all of the 3PH coefficients.

In Figure 5.19, the AFUE change has no influence on all of the 3PC coefficients. In addition, the AFUE increases 1.2 °F of the 3PH change-point, and reduces by 0.9 kBtu of the 3PH baseload and 18.5 kBtu/°F of the 3PH slope as the AFUE increases.

In Figure 5.20, the EF change has no influence on all of the 3PC coefficients. In addition, the EF change has no influence on the 3PH slope, whereas the EF reduces by 1.2 °F of the 3PH change-point, 68.6 kBtu of the 3PH baseload as the EF increases.

In Figure 5.21, the supply duct leakage change has no influence on the 3PC change-point, whereas the supply duct leakage increases 0.3 kWh of the 3PC baseload and 0.3 kWh/°F of the 3PC slope as the supply duct leakage increases. In addition, the supply duct leakage change has no influence on the 3PH change-point and baseload, whereas the supply duct leakage increases 1.4 kBtu/°F of the 3PH slope as the supply duct leakage increases.

In Figure 5.22, the return duct leakage change has no influence on the 3PC change-point, whereas the return duct leakage reduces by 0.5 kWh of the 3PC baseload, and increases 0.8 kWh/°F of the 3PC slope as the return duct leakage increases. In addition, the return duct leakage change has no influence on the 3PH change-point, whereas the return duct leakage reduces by 0.2 kBtu of the 3PH baseload, and increases 1.3 kBtu/°F of the 3PH slope as the return duct leakage increases.

In Figure 5.23, the supply duct R-value change has no influence on the 3PC change-point and baseload, whereas the supply duct R-value reduces by 0.5 kWh/°F of the 3PC slope as the supply duct R-value increases. In addition, the supply duct R-value change has no influence on the 3PH change-point, whereas the supply duct R-value increases 0.2 kBtu of the 3PH baseload, and reduces by 1.6 kBtu/°F of the 3PH slope as the supply duct R-value increases.

In Figure 5.24, the return duct R-value change has no influence on the 3PC change-point and baseload, whereas the return duct R-value reduces by 0.1 kWh/°F of the 3PC slope as the return duct R-value increases. In addition, the return duct R-value change has no influence on the 3PH change-point and baseload, whereas the return duct R-value reduces by 0.3 kBtu/°F of the 3PH slope as the return duct R-value increases.

In Figure 5.25, the WWR change for south has no influence on the 3PC change-point, whereas the WWR for south increases 1.4 kWh of the 3PC baseload and 0.1 kWh/°F of the 3PC slope as the WWR for south increases. In addition, the WWR change for south has no influence on the 3PH change-point and baseload, whereas the WWR for south increases 0.7 kBtu/°F of the 3PH slope as the WWR for south increases.

In Figure 5.26, the WWR change for east has no influence on the 3PC change-point, whereas the WWR for east increases 0.9 kWh of the 3PC baseload and 0.2 kWh/°F of the 3PC slope as the WWR for east increases. In addition, the WWR change for east has no influence on the 3PH change-point, whereas the WWR for east increases 0.4 kBtu of the 3PH baseload and 1.0 kBtu/°F of the 3PH slope as the WWR for east increases.

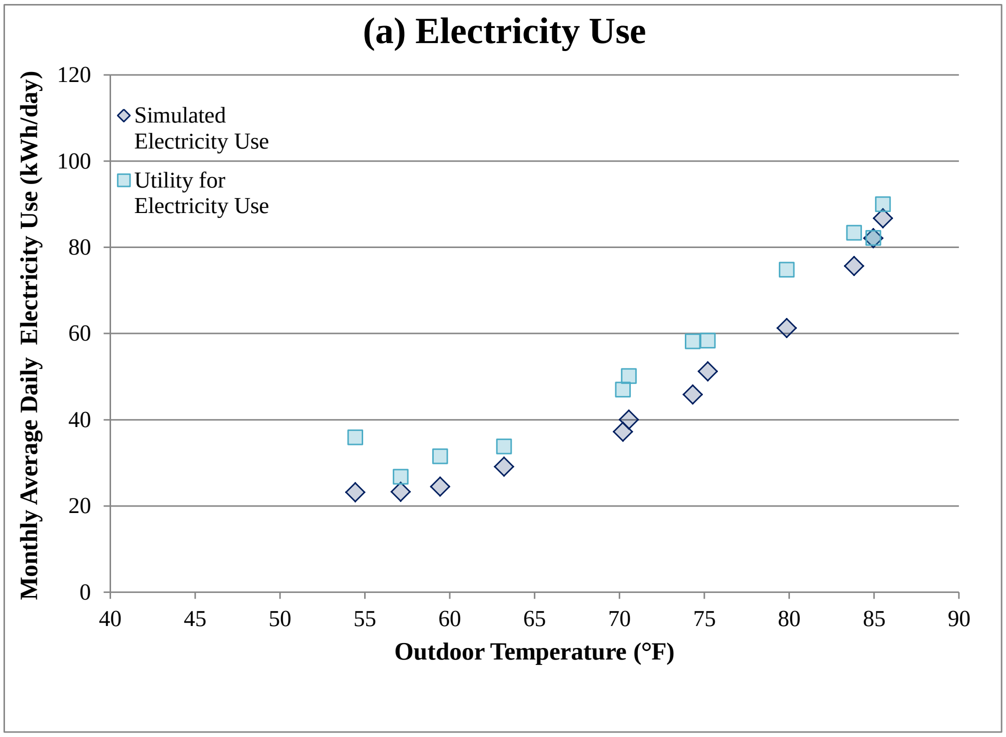
In Figure 5.27, the WWR change for west has no influence on the 3PC change-point, whereas the WWR for west increases 0.3 kWh of the 3PC baseload and 0.2 kWh/°F of the 3PC slope as the WWR for west increases. In addition, the WWR change for west has no influence on the 3PH change-point, whereas the WWR for west increases 0.5 kBtu of the 3PH baseload and 2.1 kBtu/°F of the 3PH slope as the WWR for west increases.

In Figure 5.28, the WWR change for north has no influence on the 3PC change-point, whereas the WWR for north increases 0.3 kWh of the 3PC baseload and 0.3 kWh/°F of the 3PC slope as the WWR for north increases. In addition, the WWR change for north has no influence on the 3PH change-point, whereas the WWR for north increases 0.5 kBtu of the 3PH baseload and 2.2 kBtu/°F of the 3PH slope as the WWR for north increases.

More details of the sensitivity analysis are explained in followings.

Table 5.4 through Table 5.6 and Figure 5.30 present the result of the most influential simulation parameters for each 3P coefficient. In order to obtain this result, the procedure described in Section 4.2.4.2 was used. As a first step, the result of the percentage ranges for 3PC and 3PH coefficients of all 20 simulation parameters when each parameter value was varied from 50% to 150% of the nominal value was calculated using equation (4.17) as shown in 8th column in Table 5.4. The 5th, 6th and 7th columns in Table 5.4 show the corresponding coefficient values when the minimum, maximum and nominal values of each simulation input parameter were run, respectively.

Next, the results of the percentage of 3PC and 3PH coefficients for simulation parameters were calculated as shown in Table 5.5. For this calculation, the percentage range in 8th column in Table 5.4 for the selected 3P coefficient for the selected parameter was divided by the sum of the percentage range for the corresponding 3P coefficient. For example, in order to obtain the percentage of 3PC change-point coefficient for wall R-value parameter (i.e., 0.0% in Table 5.5), the percentage range of 3PC change-point



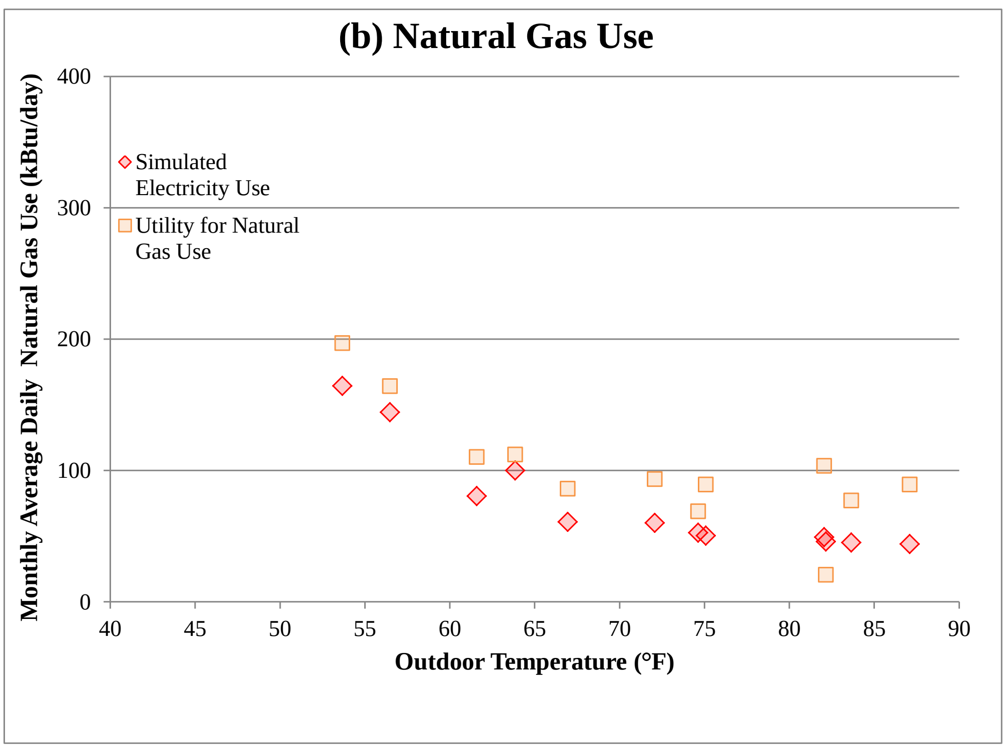


Figure 5.7 Results for the Easy-to-use House #1 Simulation and the Monthly Utility Bills for: (a) Electricity Use and (b) Natural Gas Use

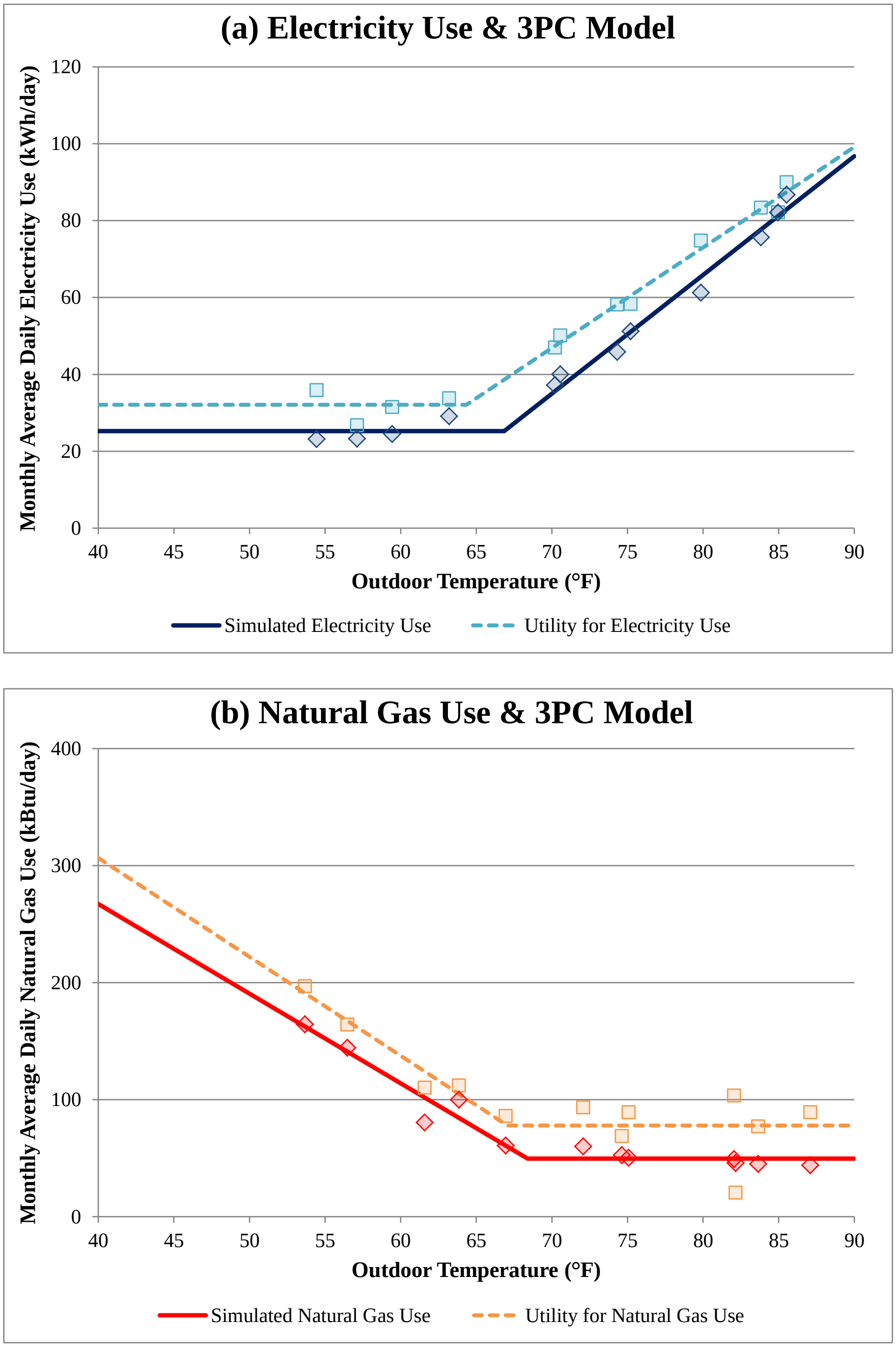


Figure 5.8 Results for the Easy-to-use House #1 Simulation and Monthly Utility Bills, and Corresponding 3P Regression Models for: (a) Electricity Use and (b) Natural Gas Use

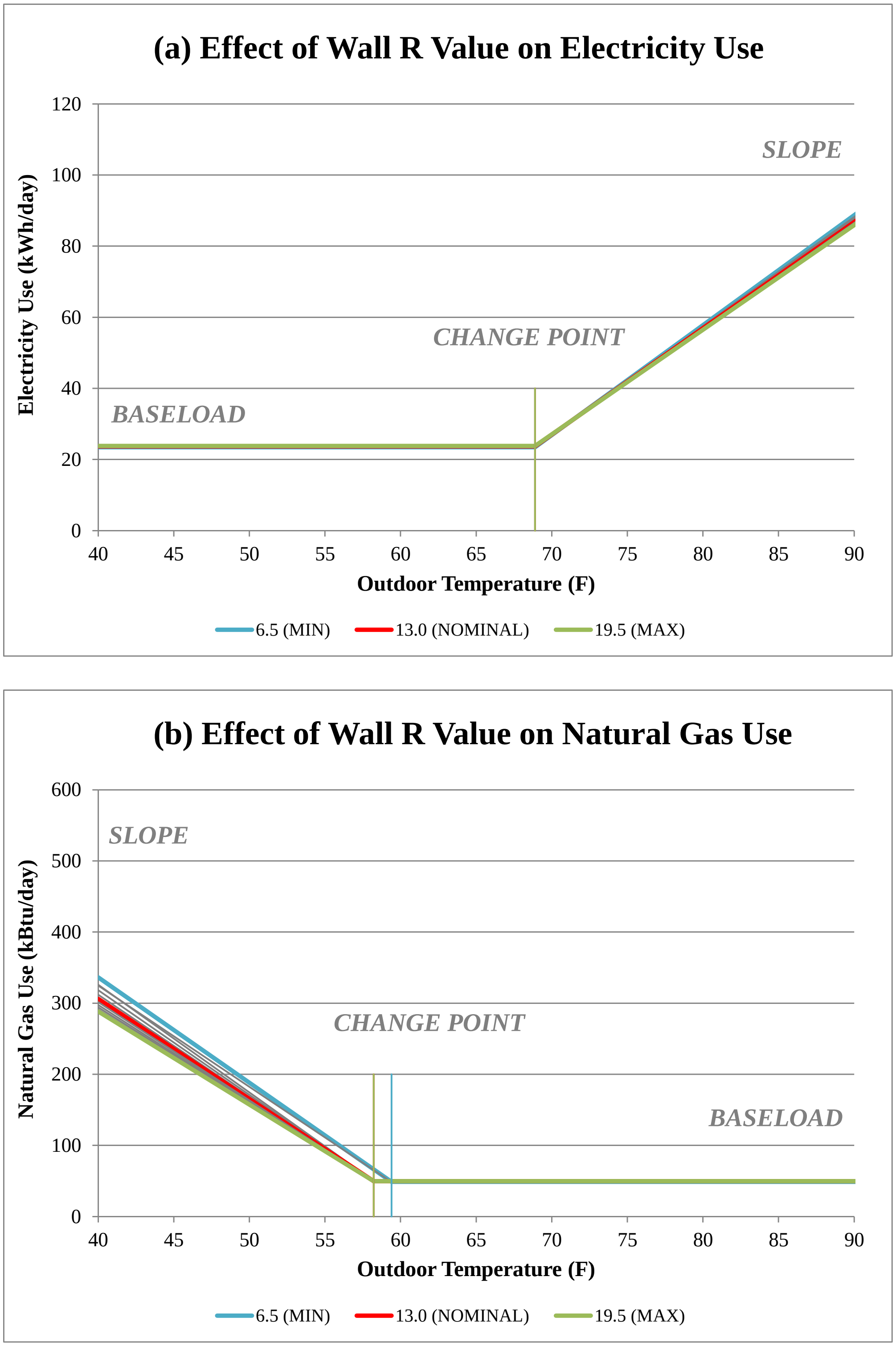
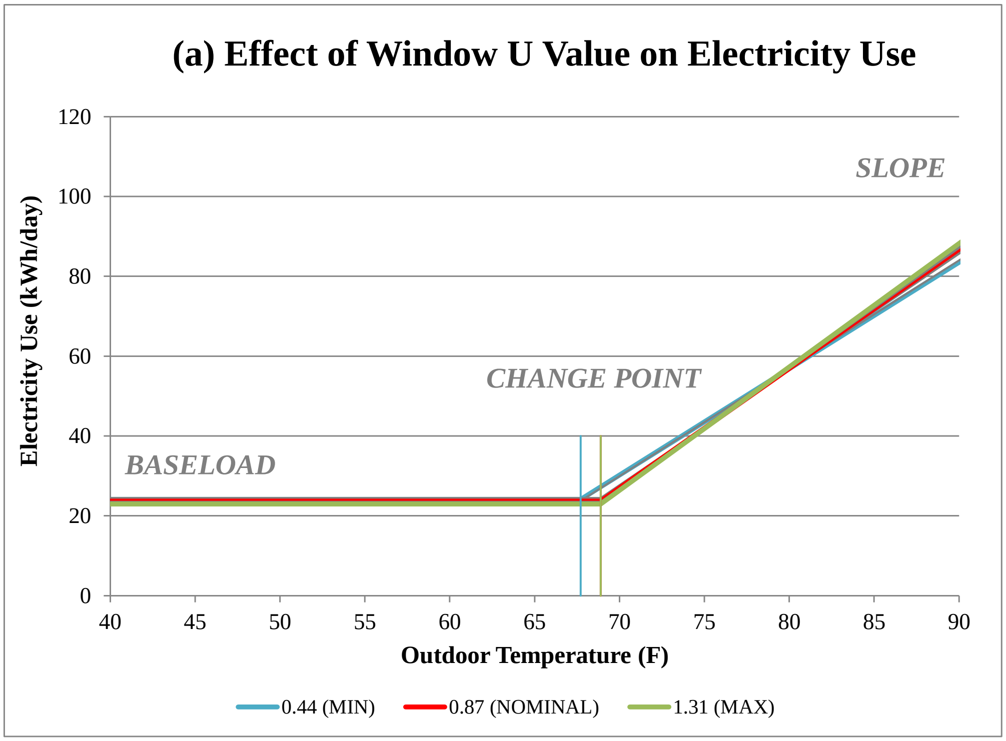


Figure 5.9 Sensitivity Test Results: Effect of Wall R-value on (a) Electricity Use and (b) Natural Gas Use



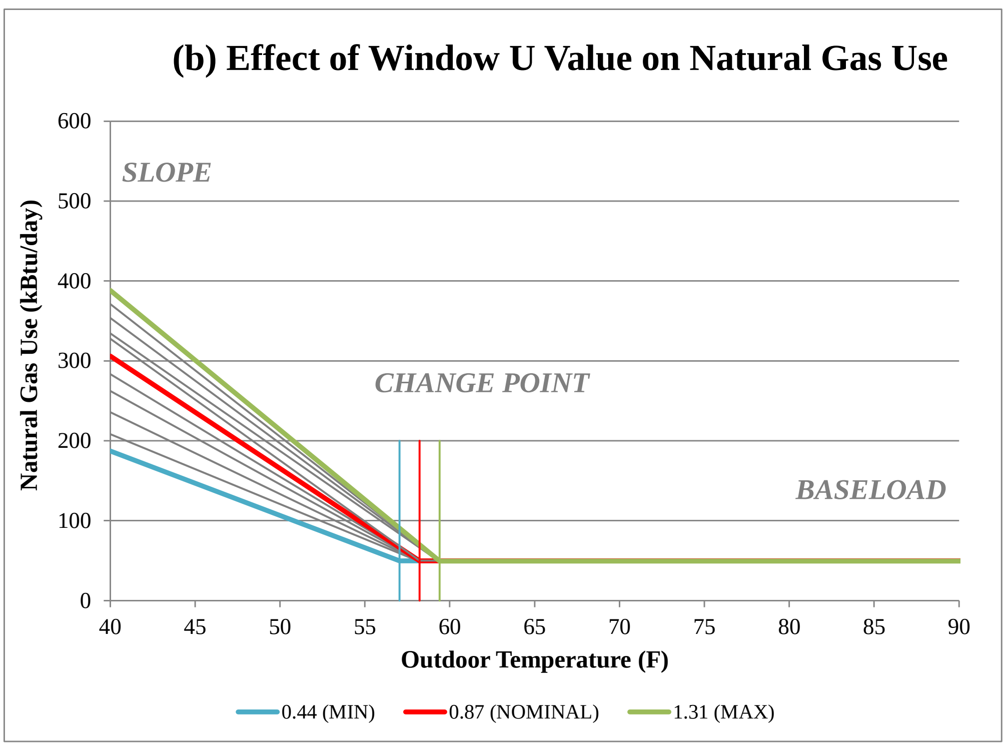
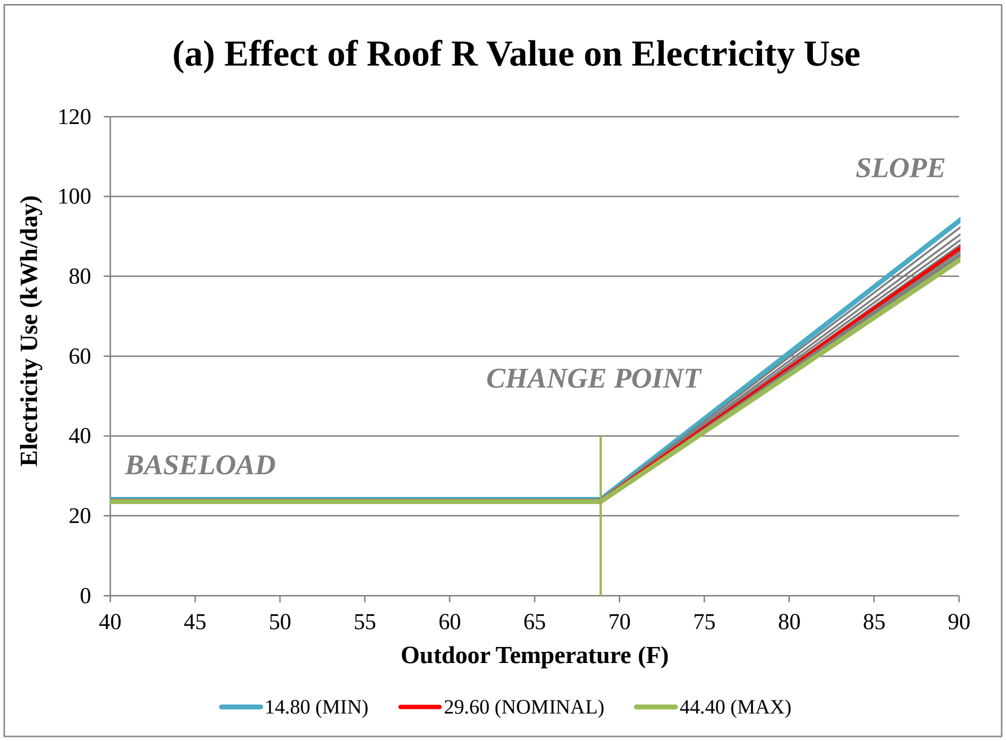


Figure 5.10 Sensitivity Test Results: Effect of Window U-value on (a) Electricity Use and (b) Natural Gas Use



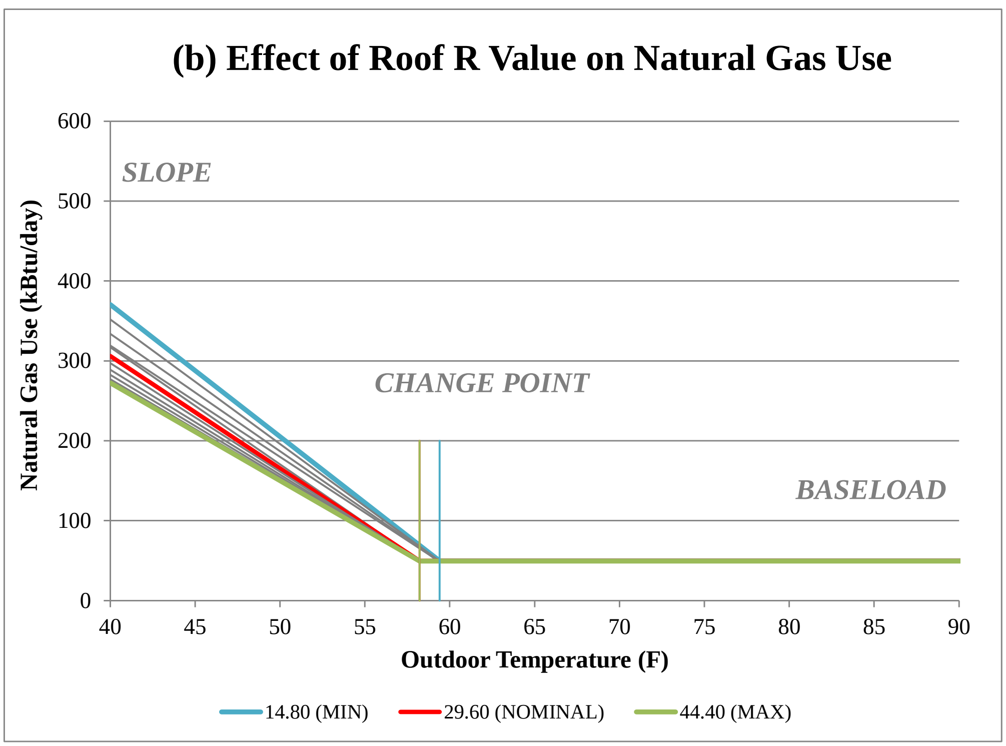
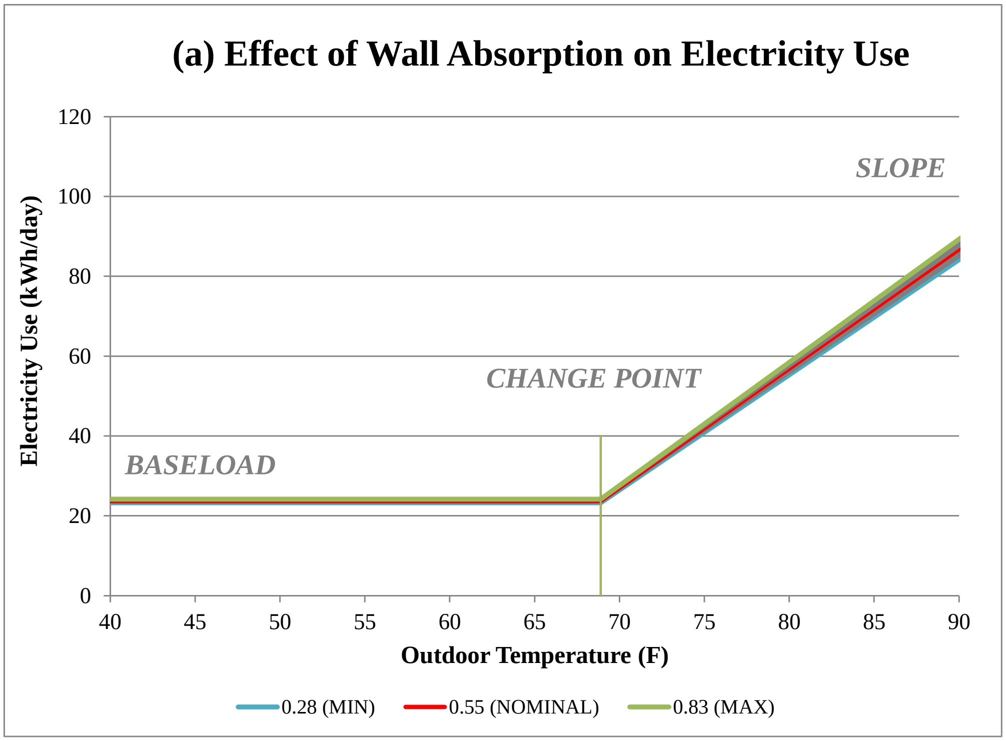


Figure 5.11 Sensitivity Test Results: Effect of Roof R-value on (a) Electricity Use and (b) Natural Gas Use



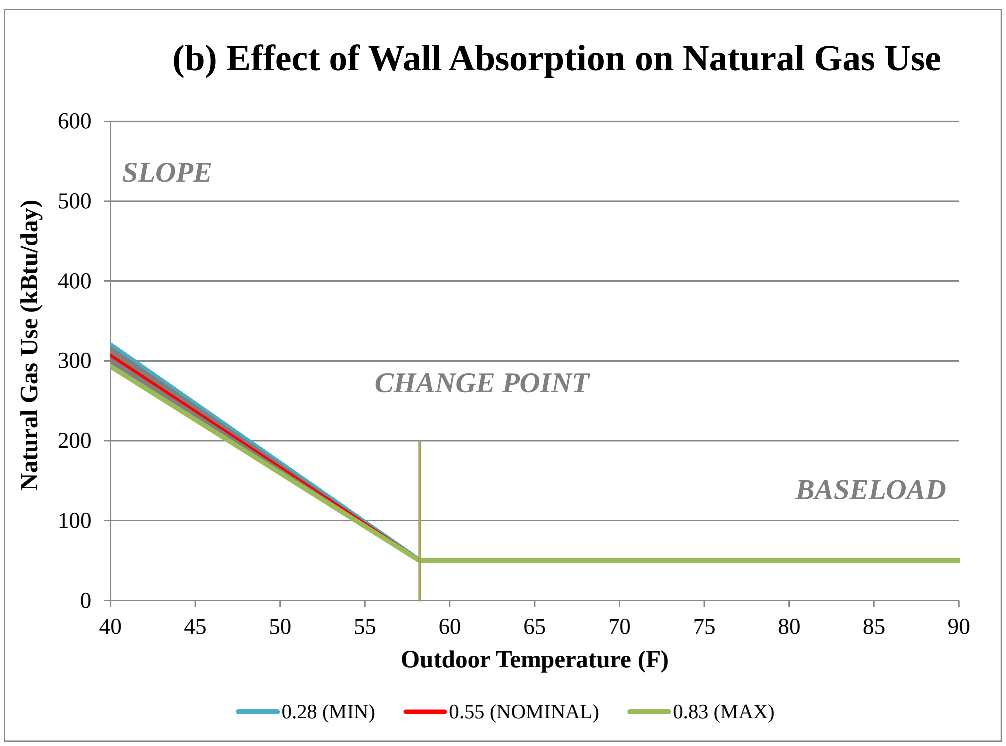


Figure 5.12 Sensitivity Test Results: Effect of Wall Absorption on (a) Electricity Use and (b) Natural Gas Use

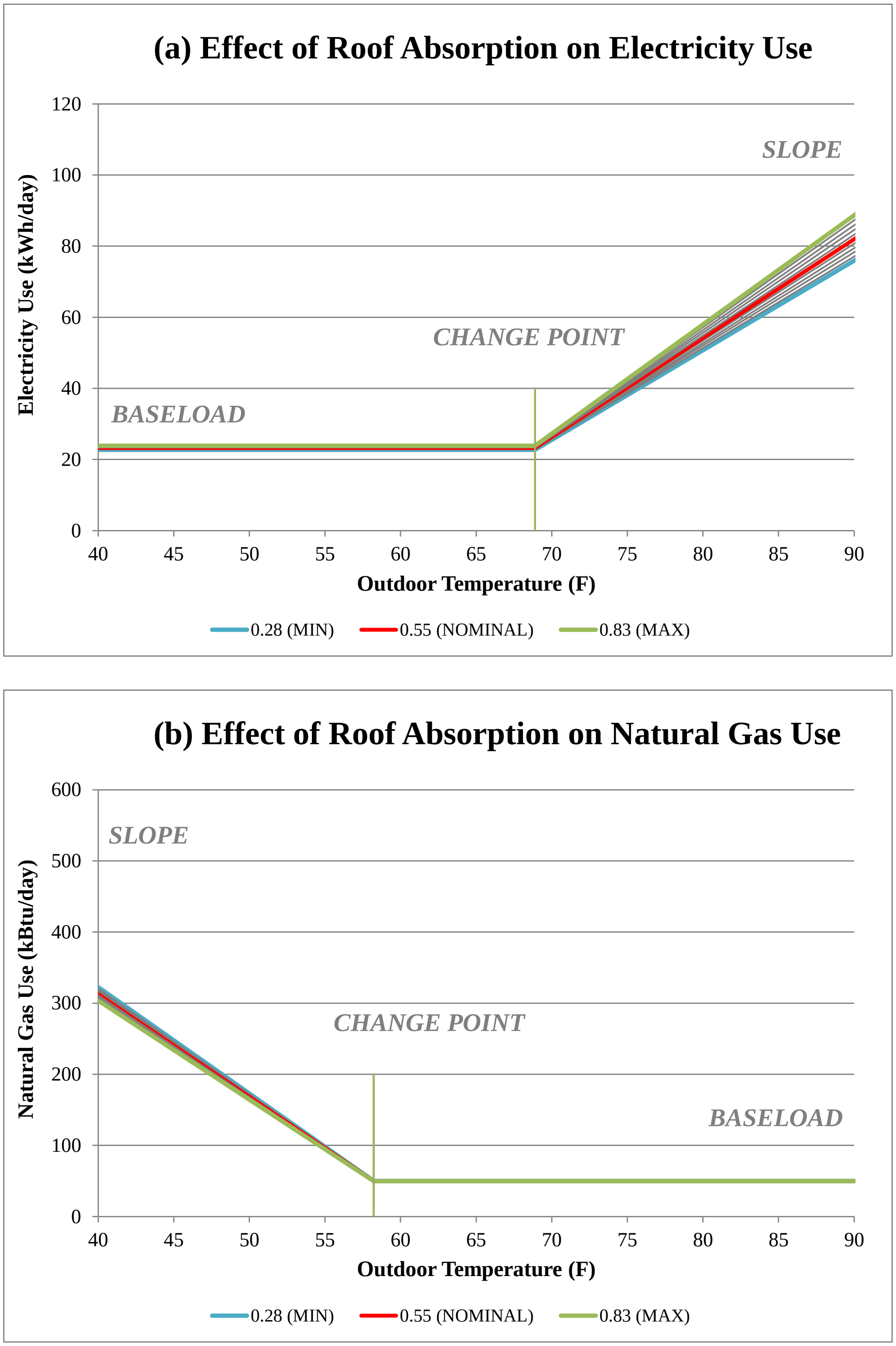


Figure 5.13 Sensitivity Test Results: Effect of Roof Absorption on (a) Electricity Use and (b) Natural Gas Use

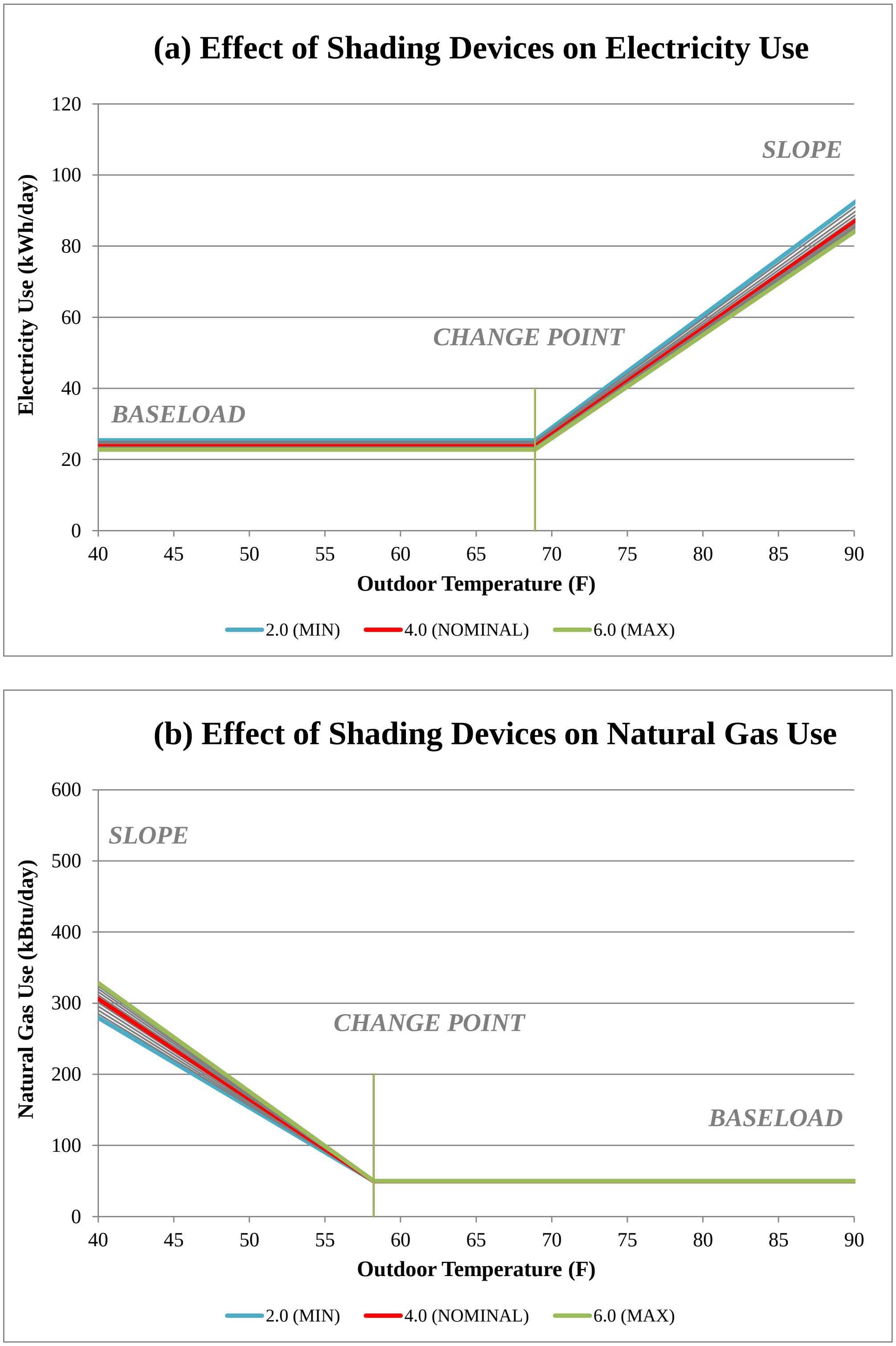
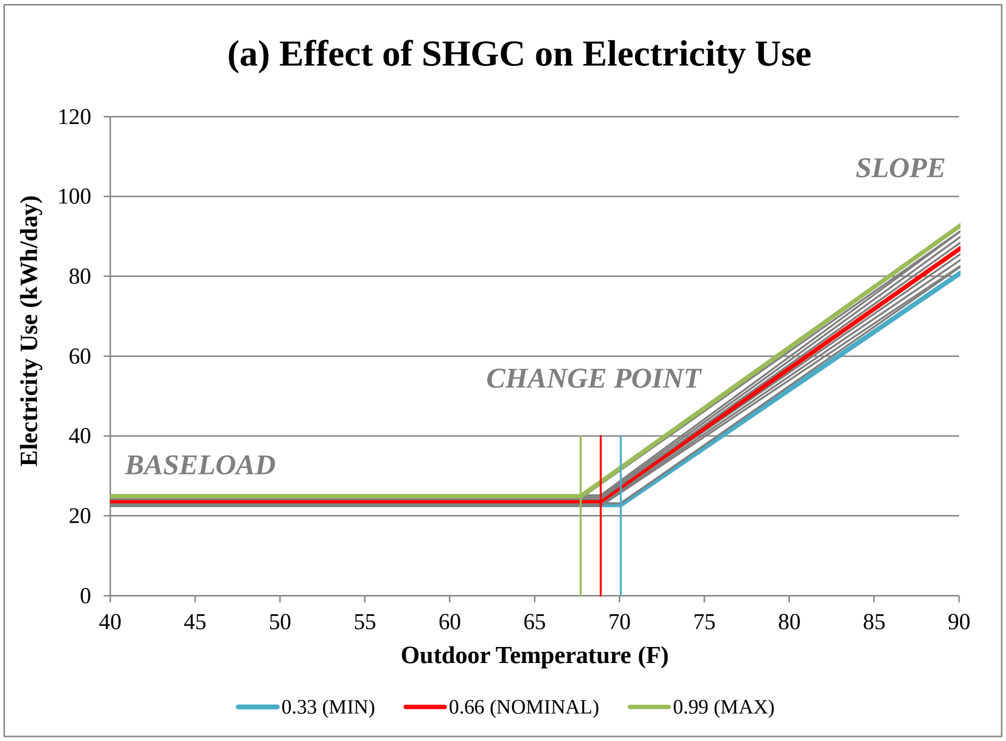


Figure 5.14 Sensitivity Test Results: Effect of Shading Devices on (a) Electricity Use and (b) Natural Gas Use



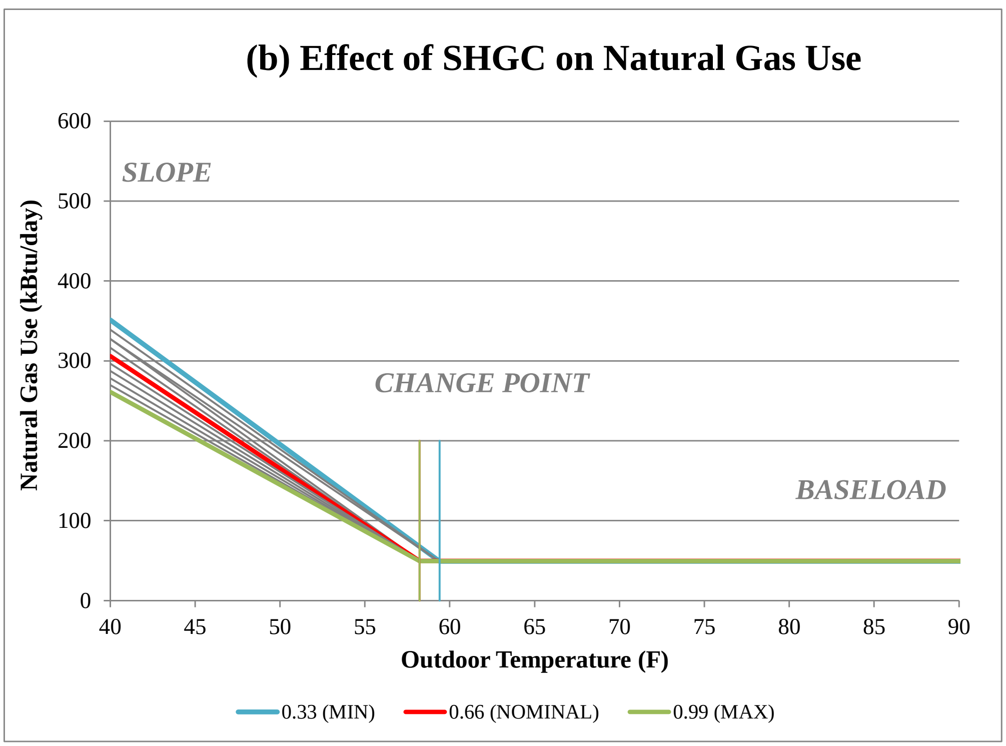
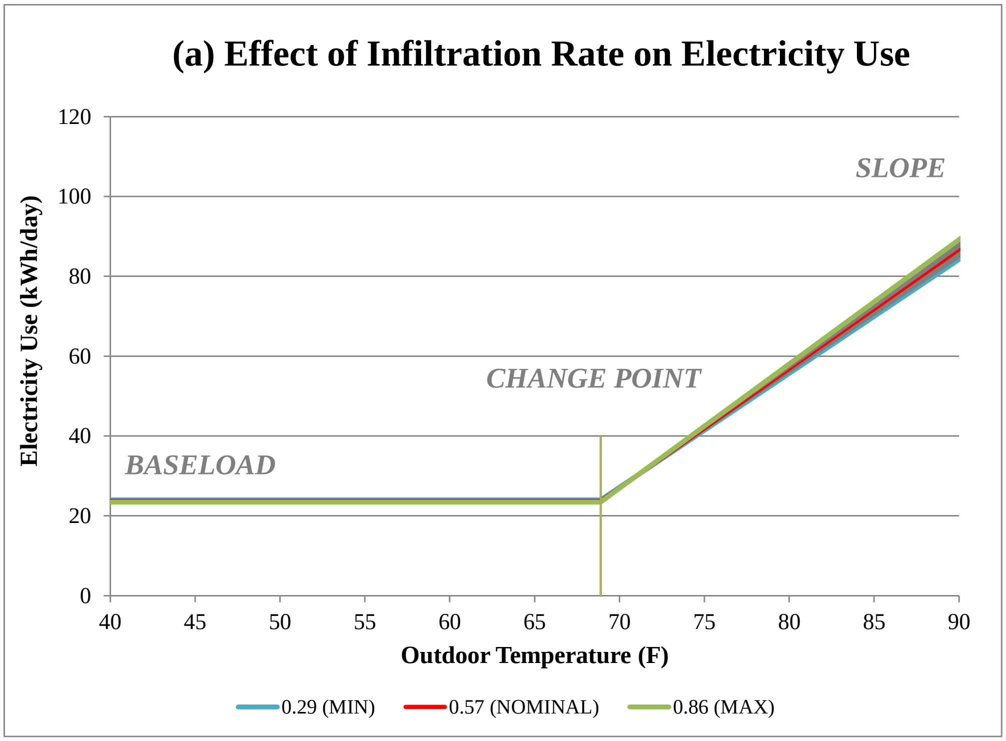


Figure 5.15 Sensitivity Test Results: Effect of SHGC on (a) Electricity Use and (b) Natural Gas Use



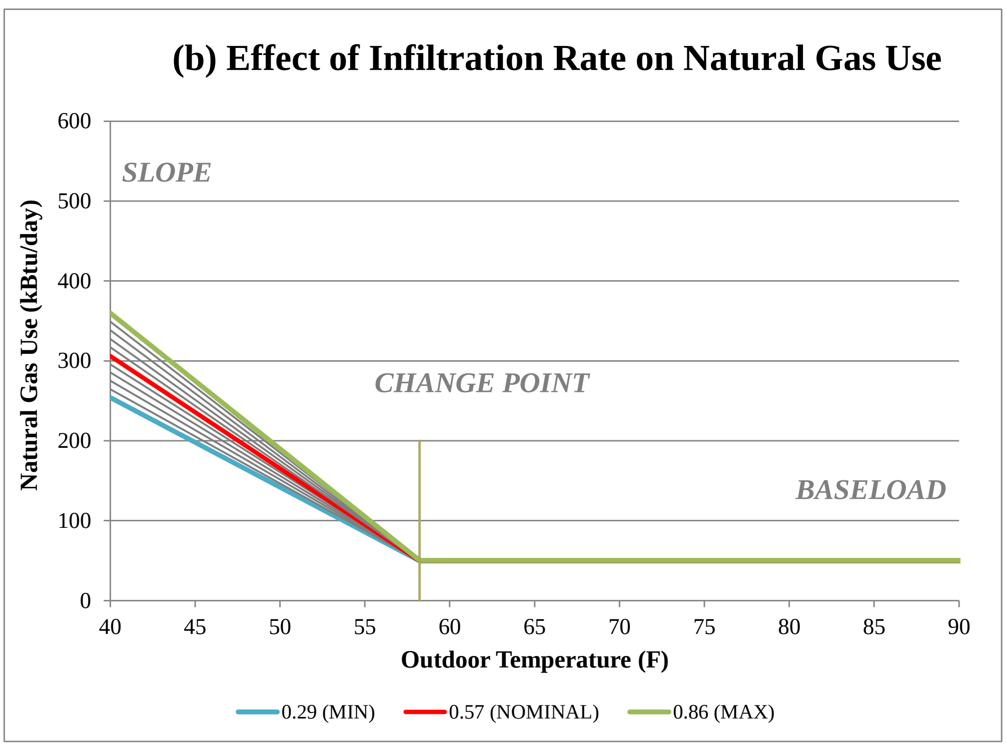
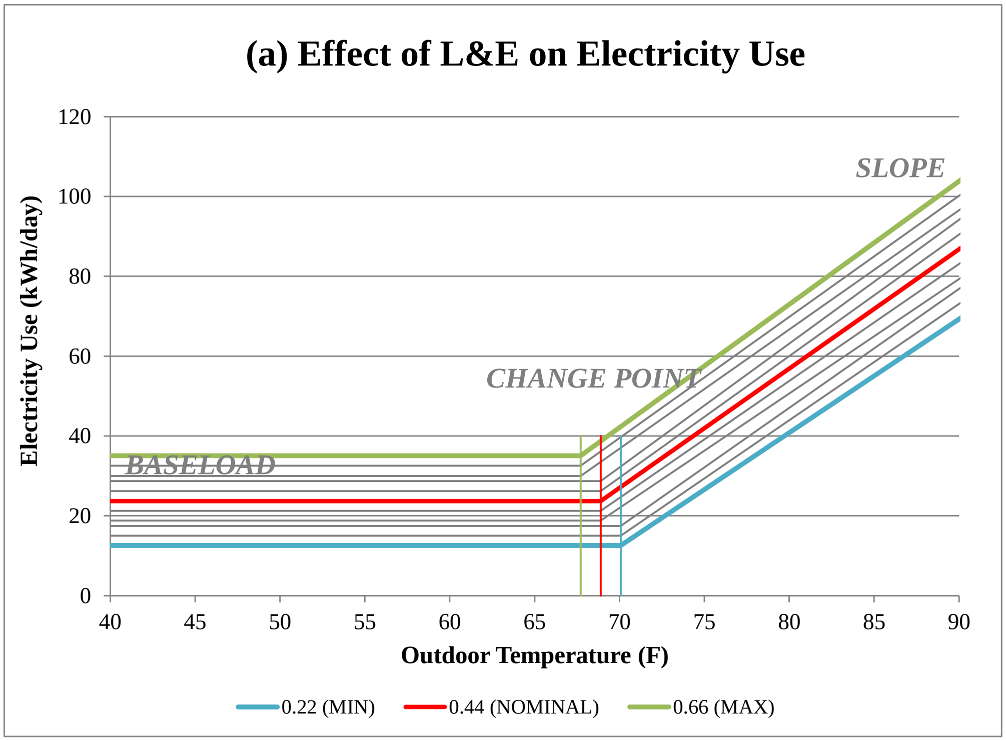


Figure 5.16 Sensitivity Test Results: Effect of Infiltration Rate on (a) Electricity Use and (b) Natural Gas Use



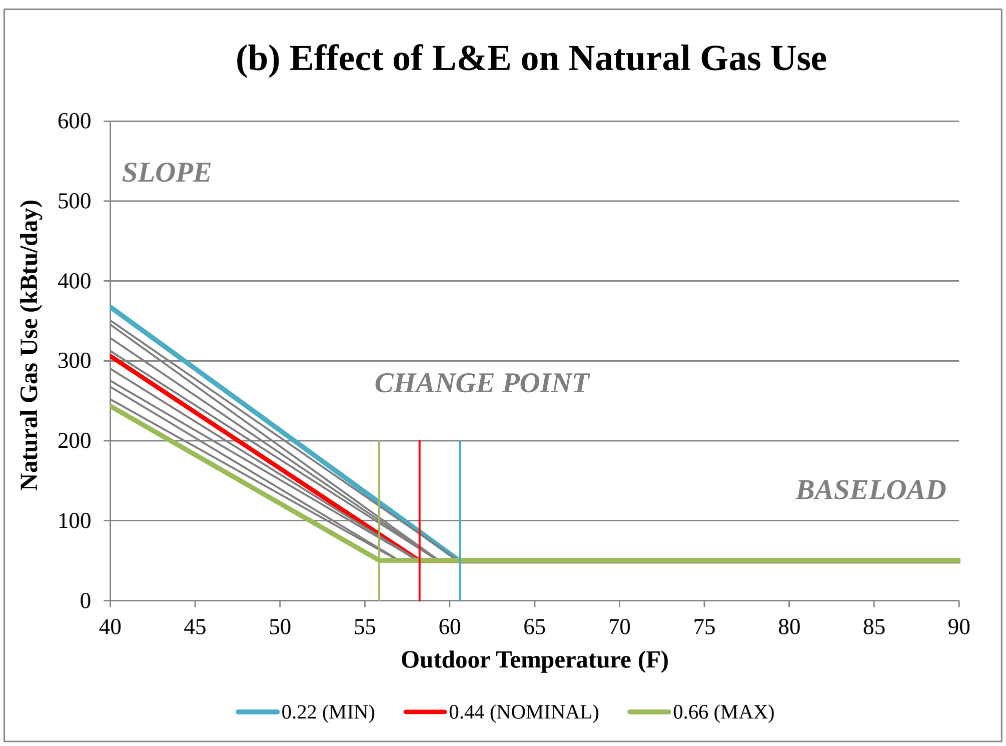
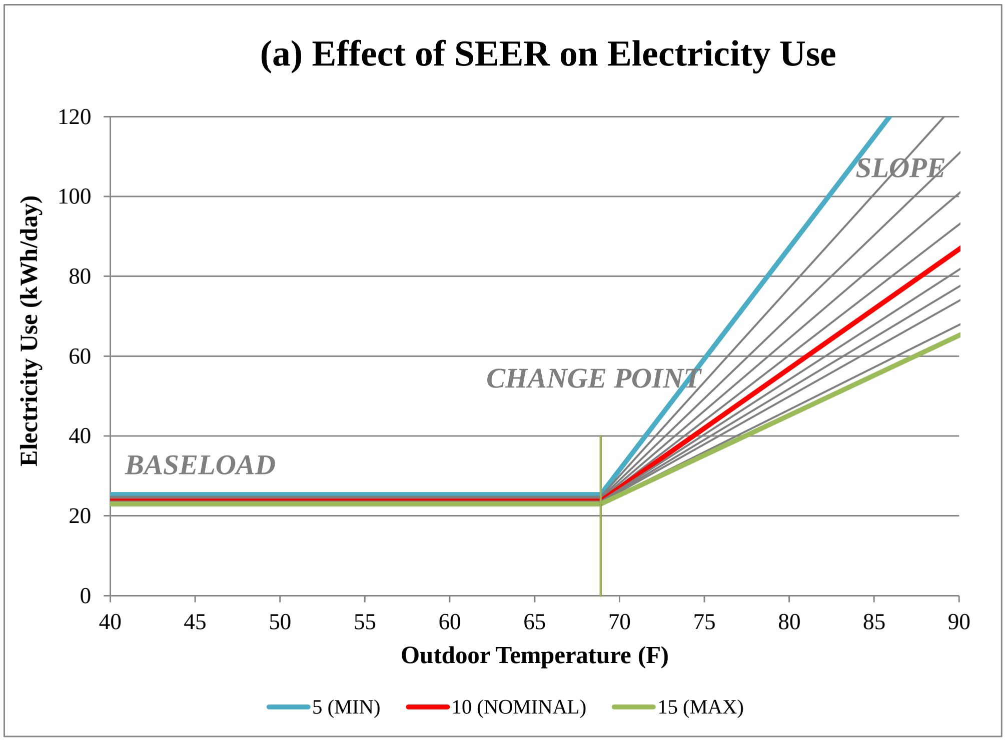


Figure 5.17 Sensitivity Test Results: Effect of L&E on (a) Electricity Use and (b) Natural Gas Use



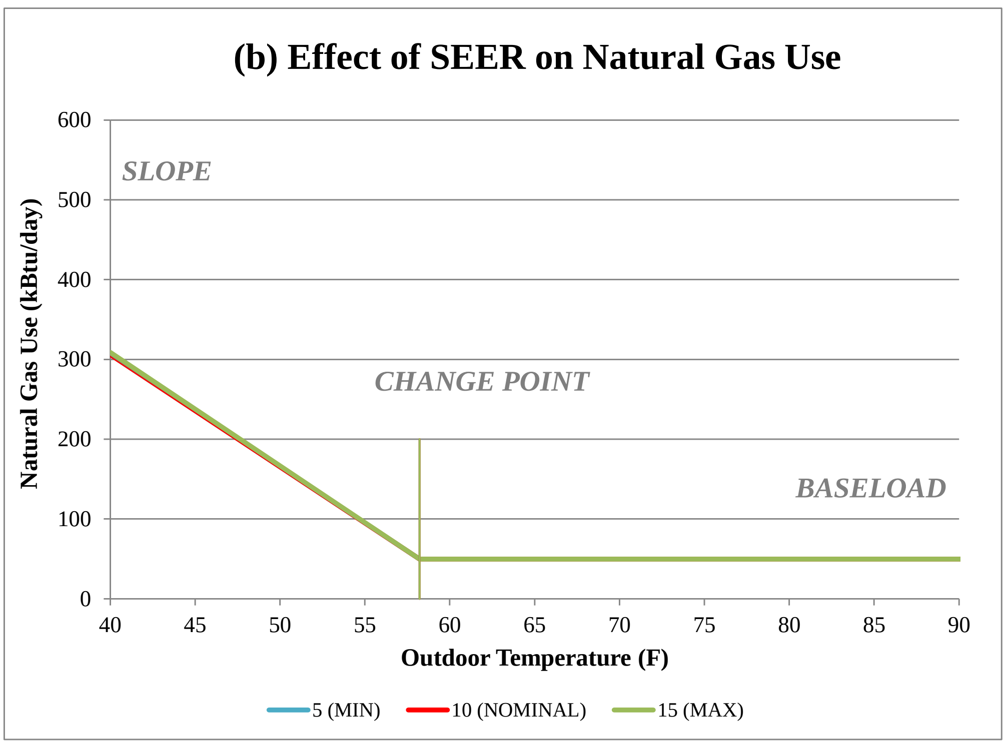
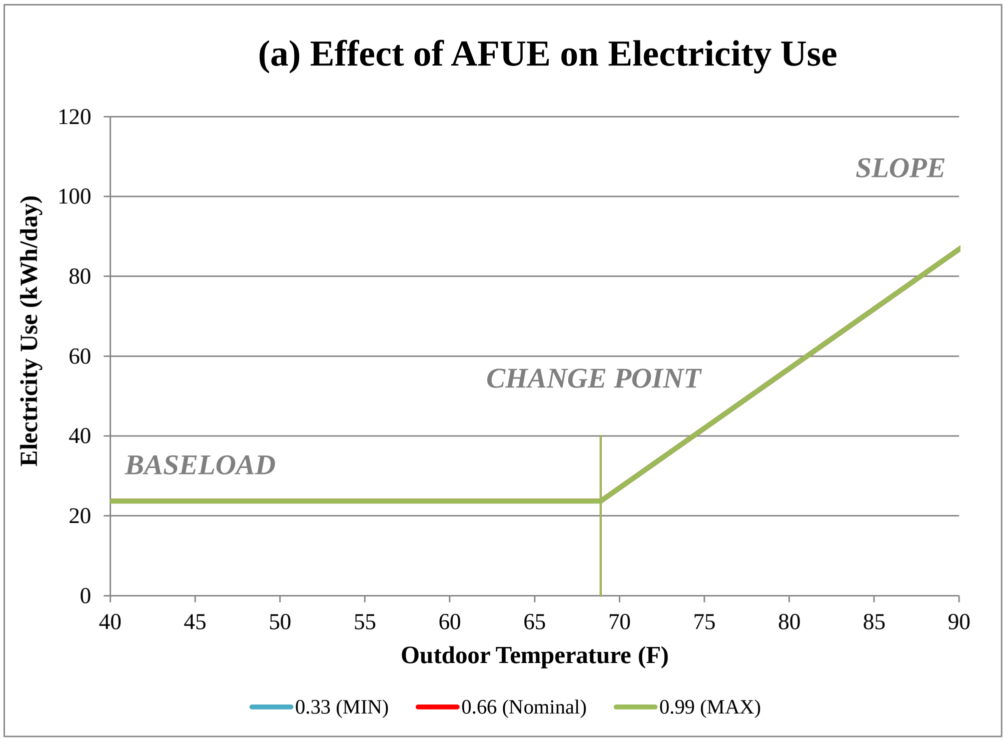


Figure 5.18 Sensitivity Test Results: Effect of SEER on (a) Electricity Use and (b) Natural Gas Use



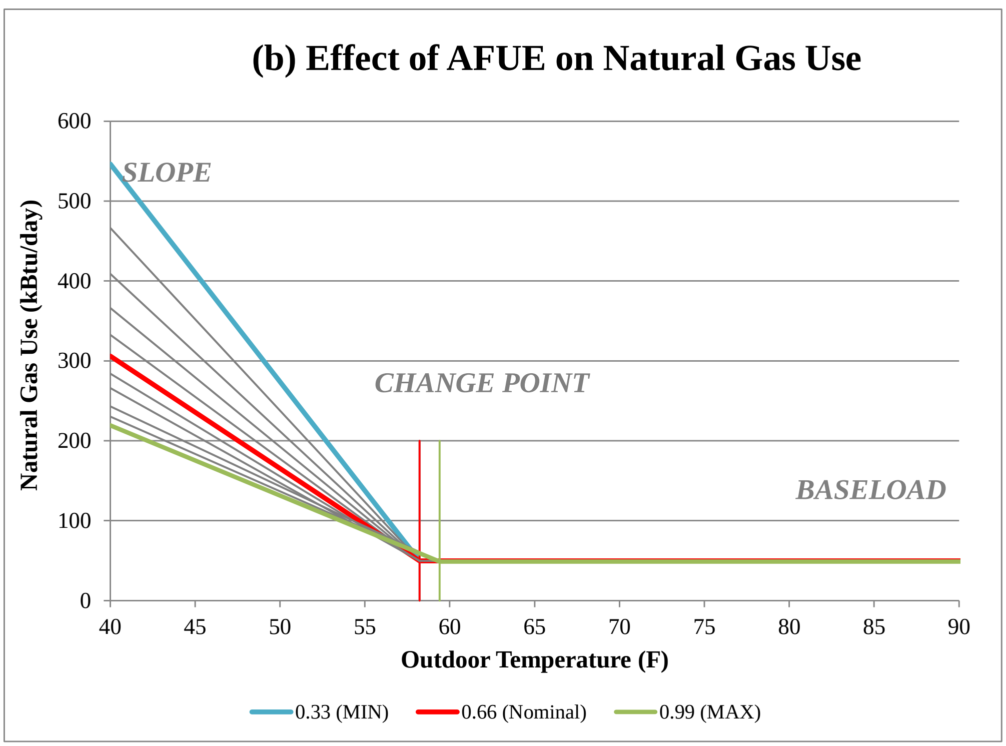
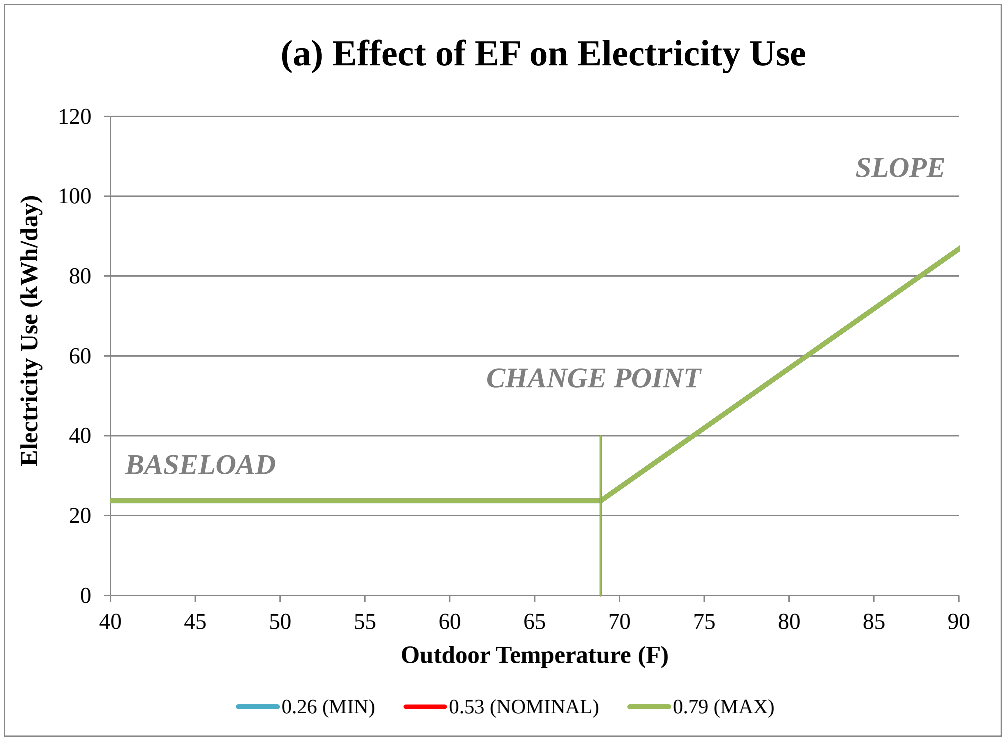


Figure 5.19 Sensitivity Test Results: Effect of AFUE on (a) Electricity Use and (b) Natural Gas Use



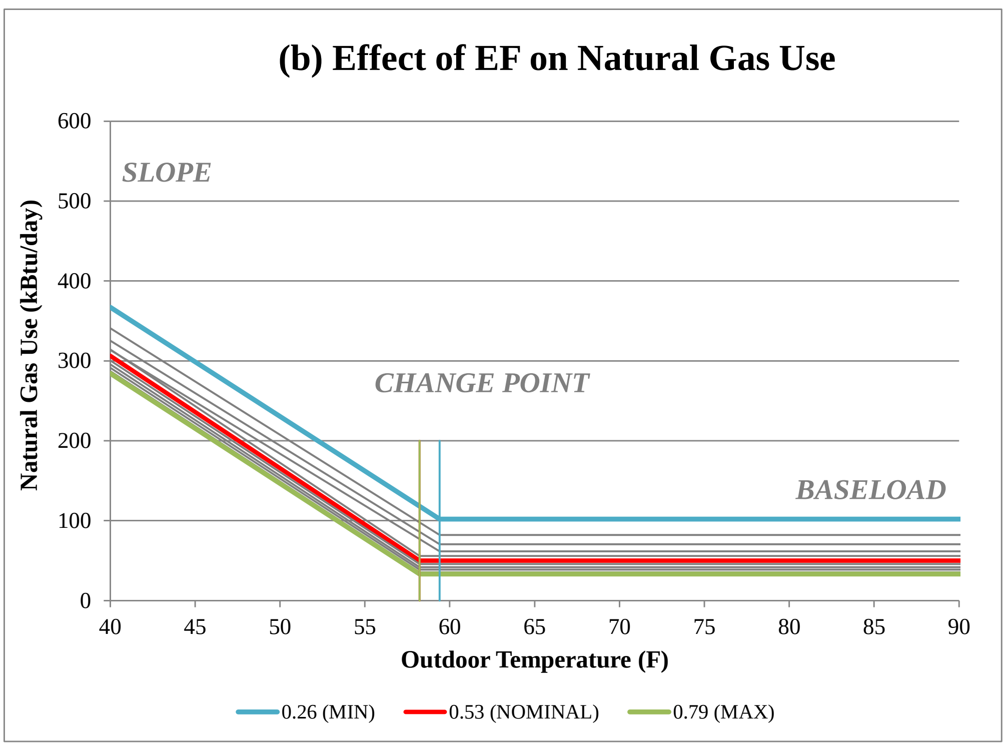


Figure 5.20 *Sensitivity Test Results: Effect of EF on (a) Electricity Use and (b) Natural Gas Use*

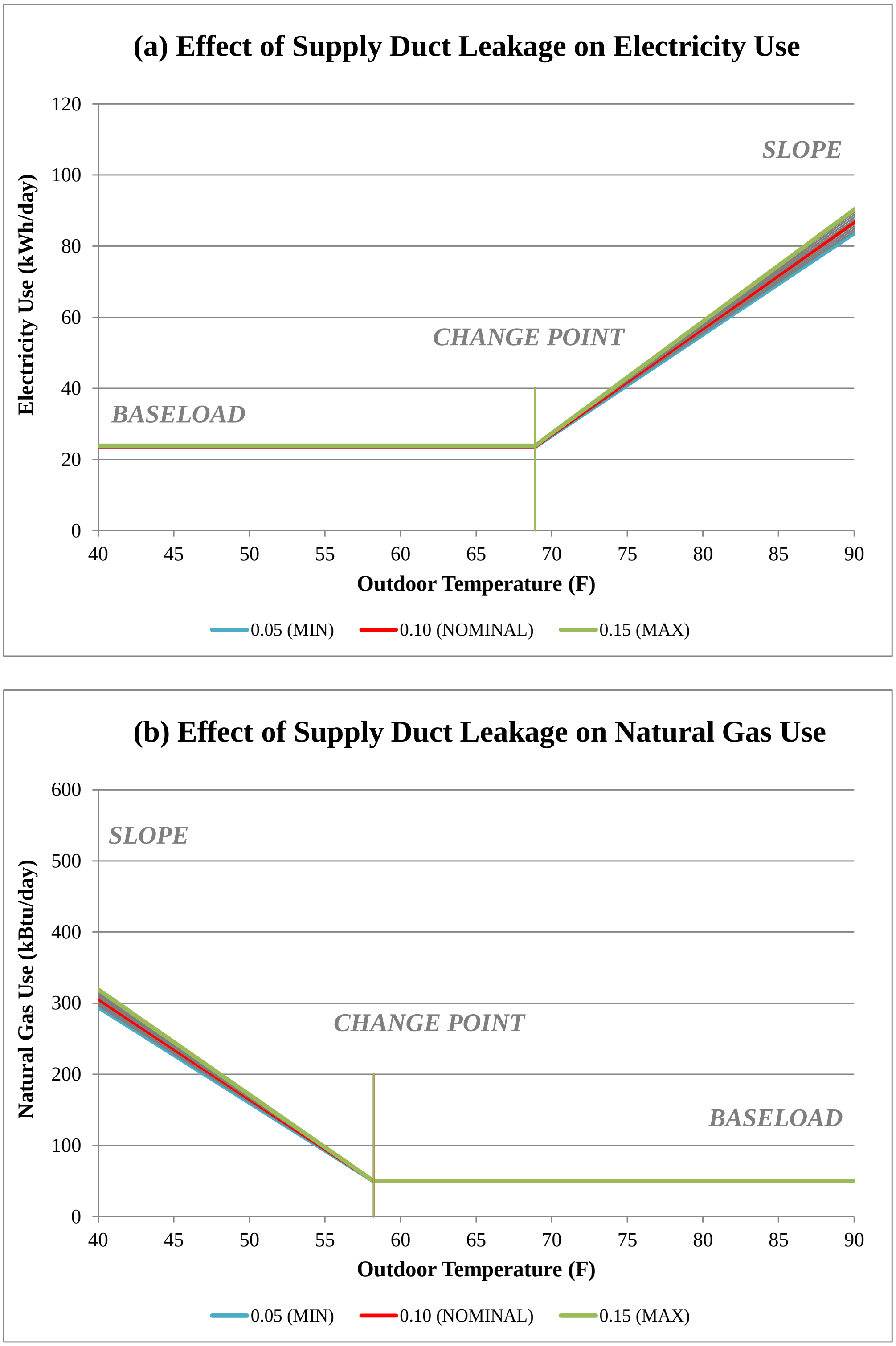
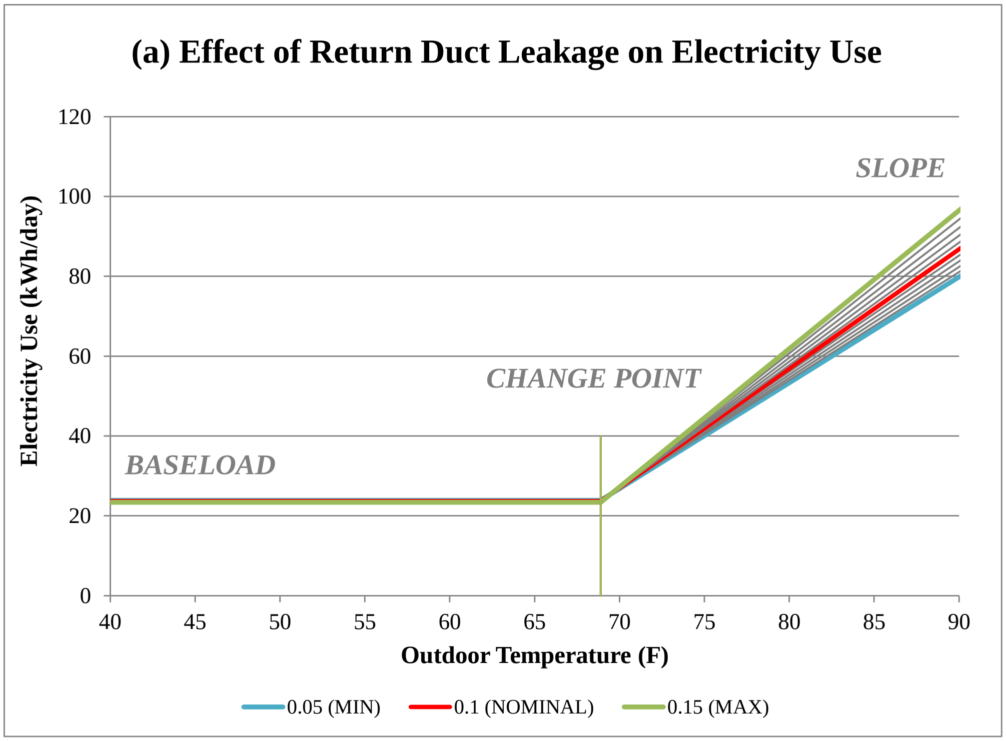


Figure 5.21 Sensitivity Test Results: Effect of Supply Duct Leakage on (a) Electricity Use and (b) Natural Gas Use



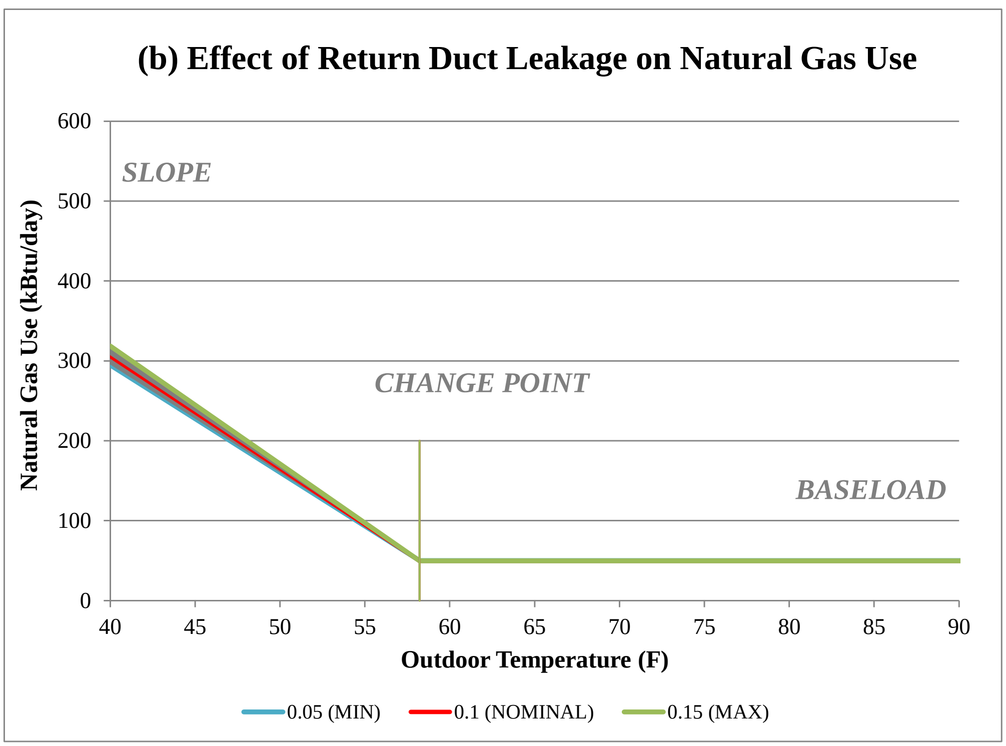


Figure 5.22 Sensitivity Test Results: Effect of Return Duct Leakage on (a) Electricity Use and (b) Natural Gas Use

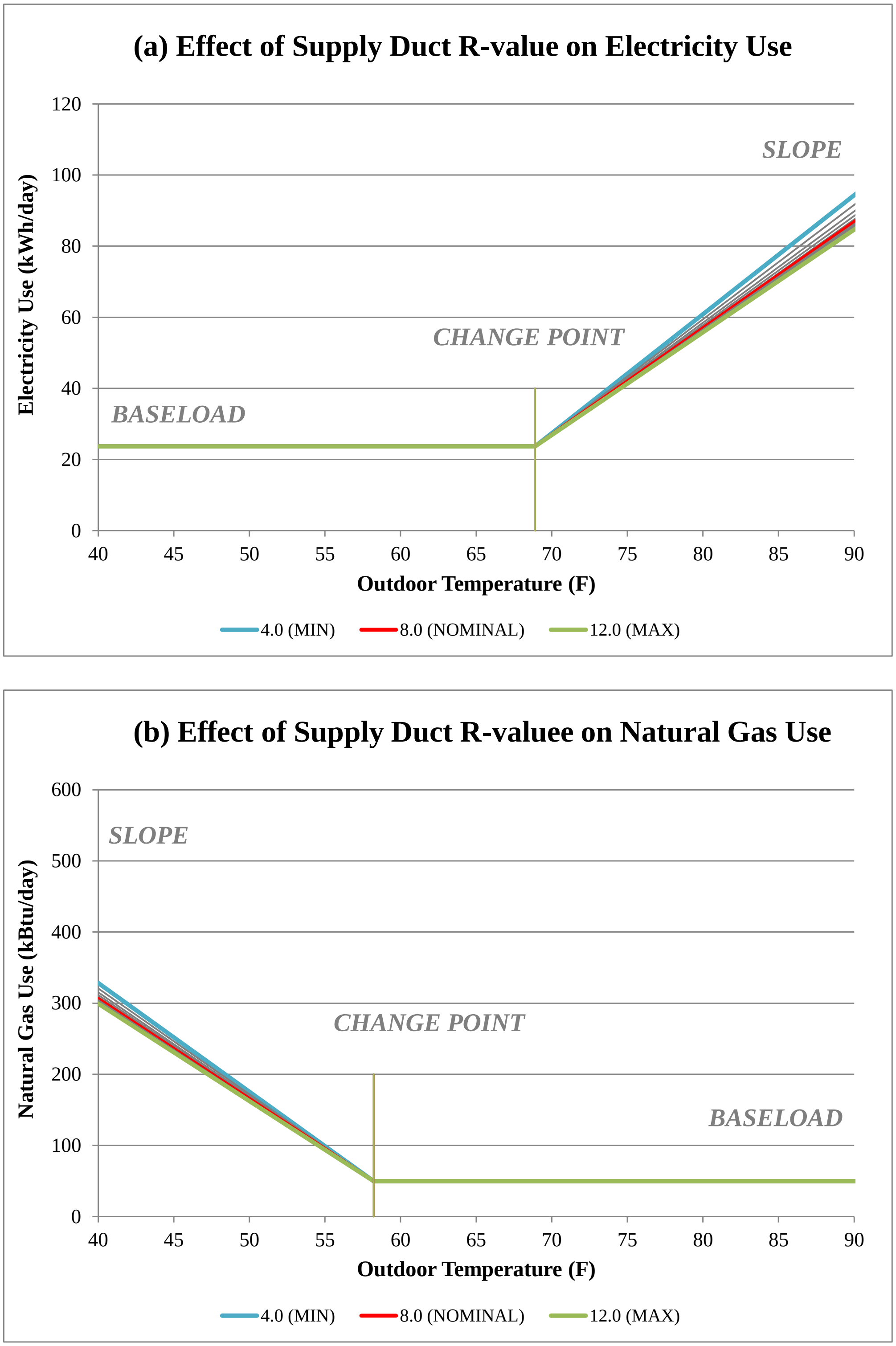
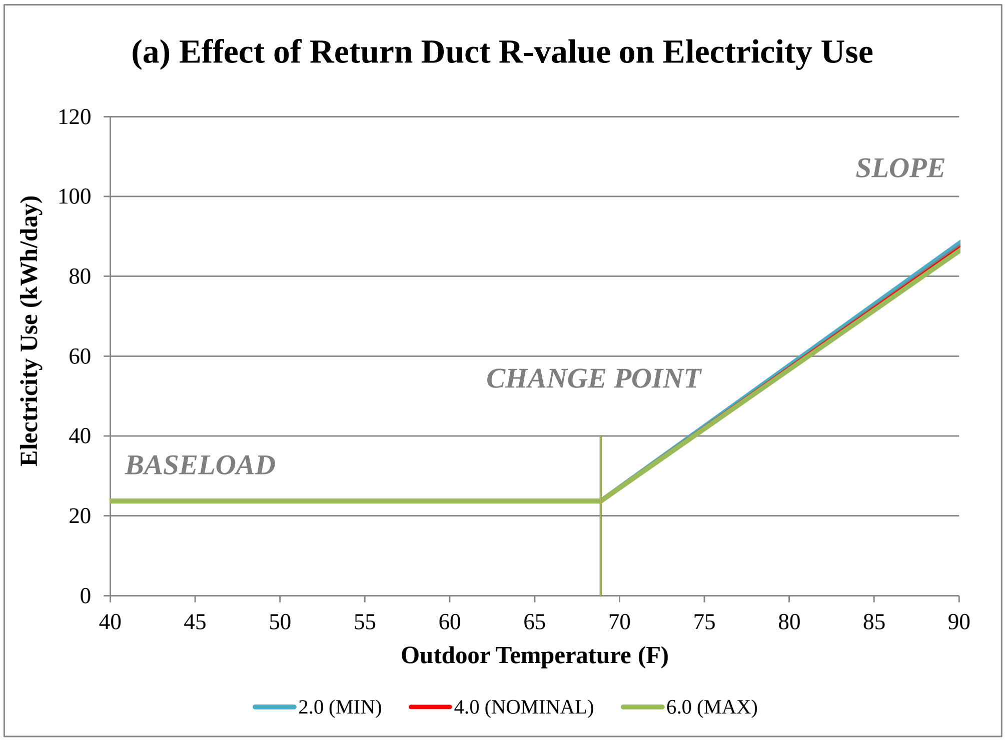


Figure 5.23 Sensitivity Test Results: Effect of Supply Duct R-value on (a) Electricity Use and (b) Natural Gas Use



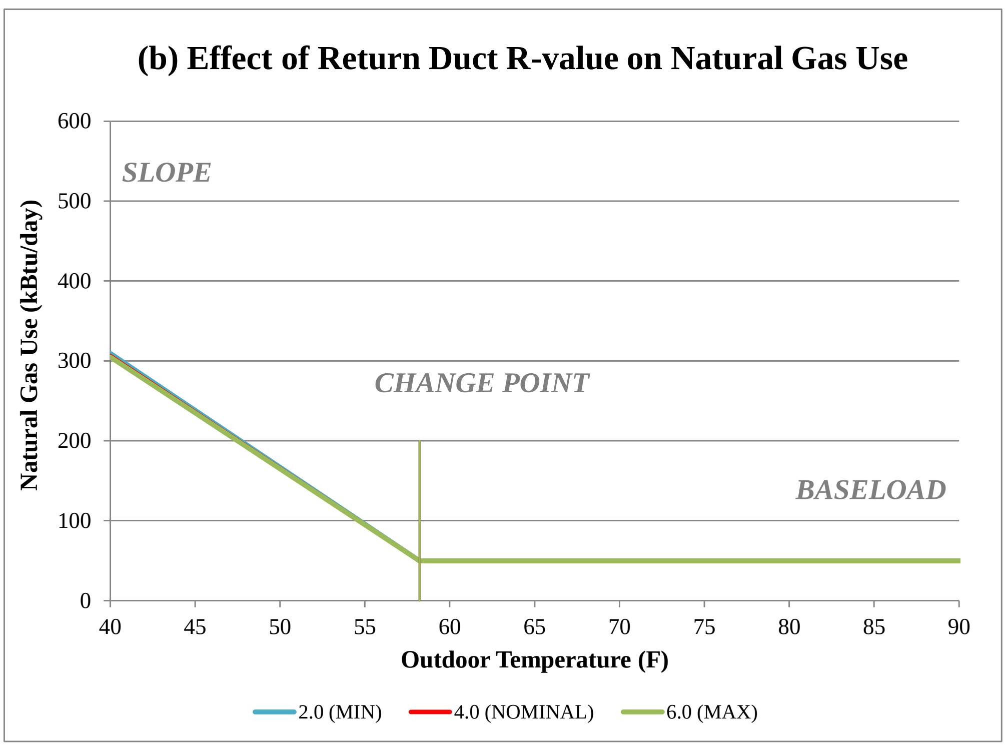
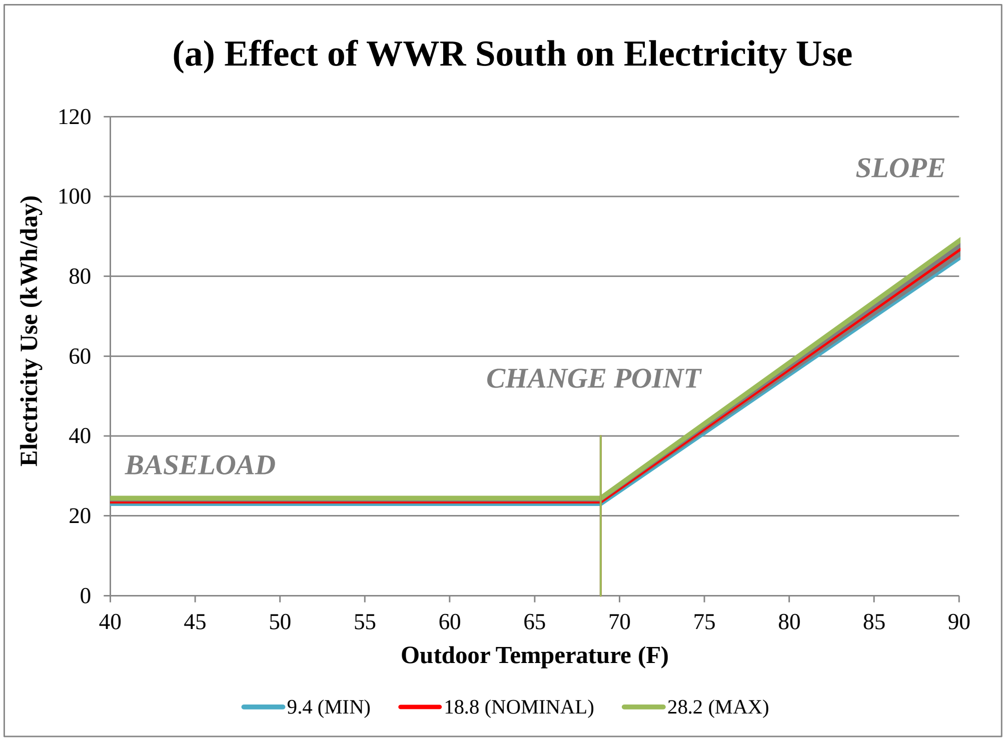


Figure 5.24 Sensitivity Test Results: Effect of Return Duct R-value on (a) Electricity Use and (b) Natural Gas Use



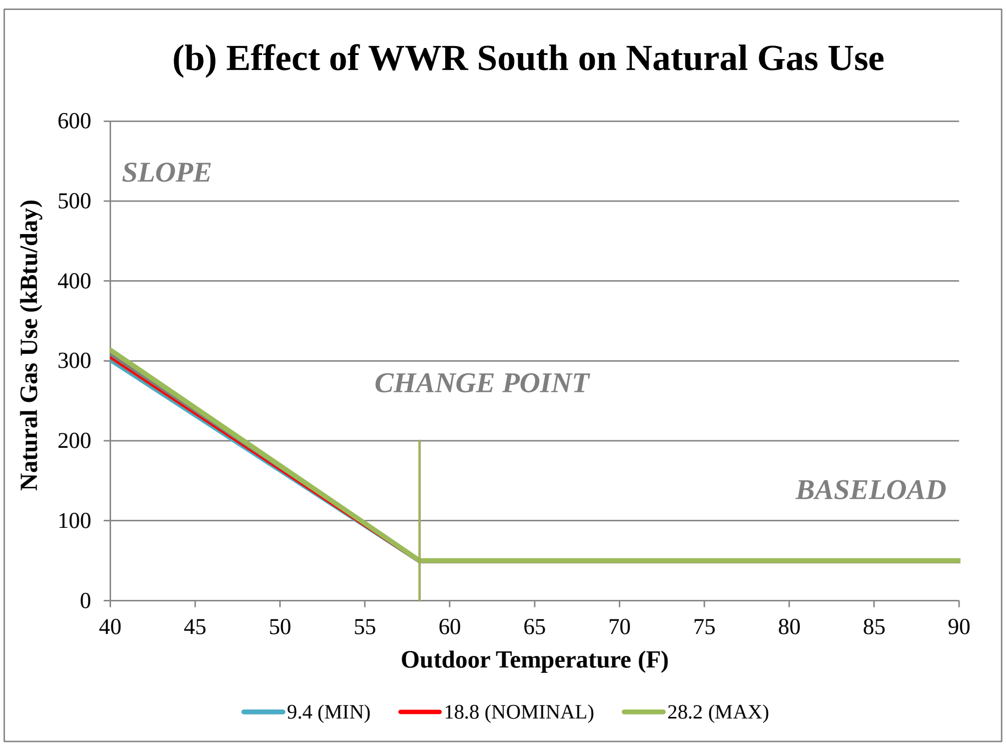


Figure 5.25 Sensitivity Test Results: Effect of WWR for South on (a) Electricity Use and (b) Natural Gas Use

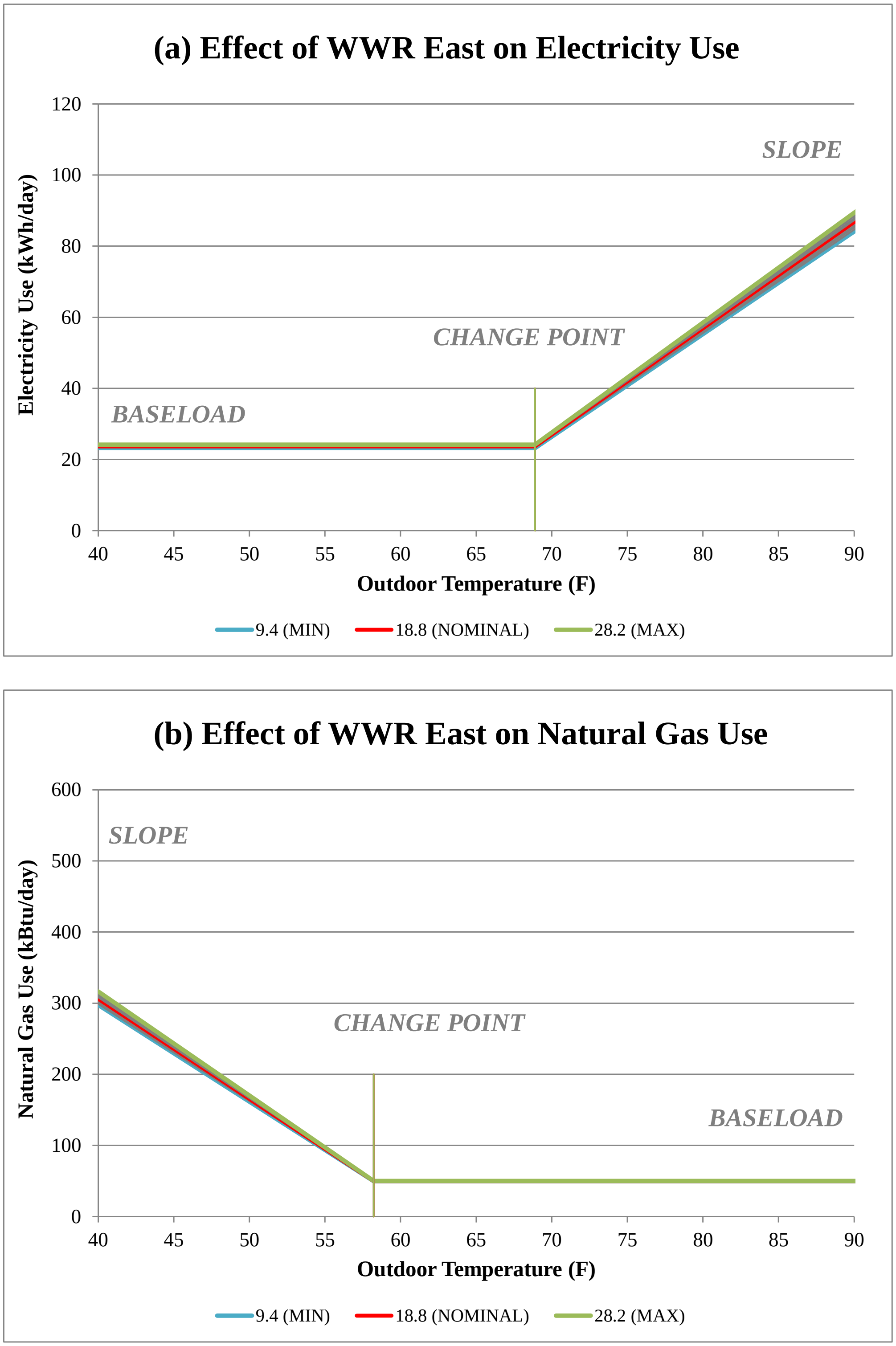
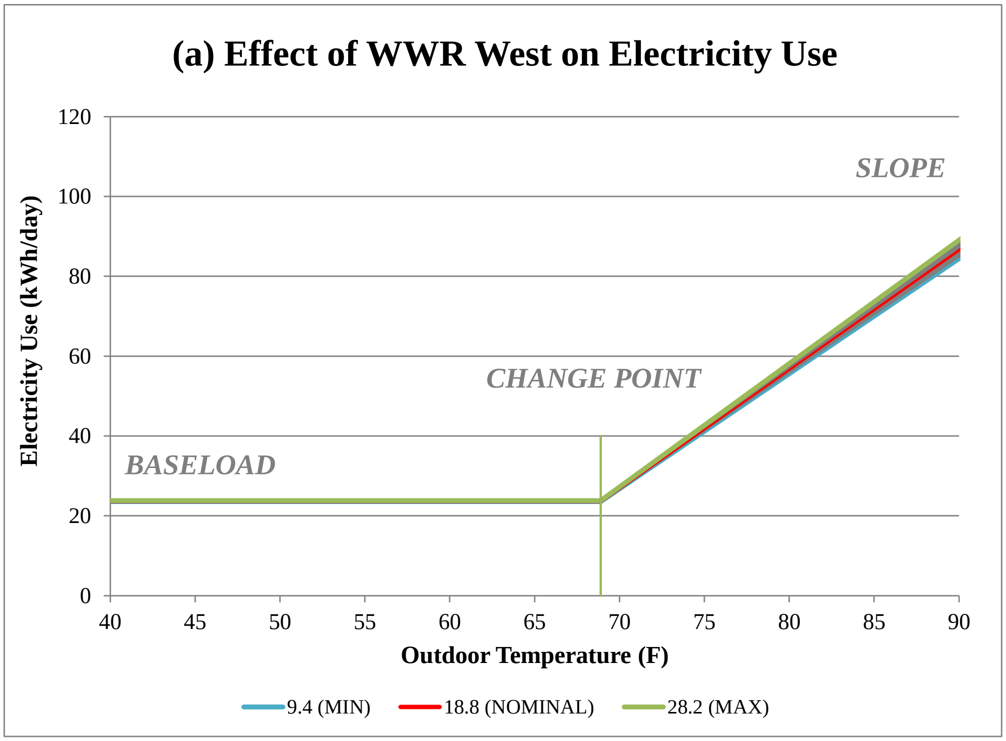


Figure 5.26 Sensitivity Test Results: Effect of WWR for East on (a) Electricity Use and (b) Natural Gas Use



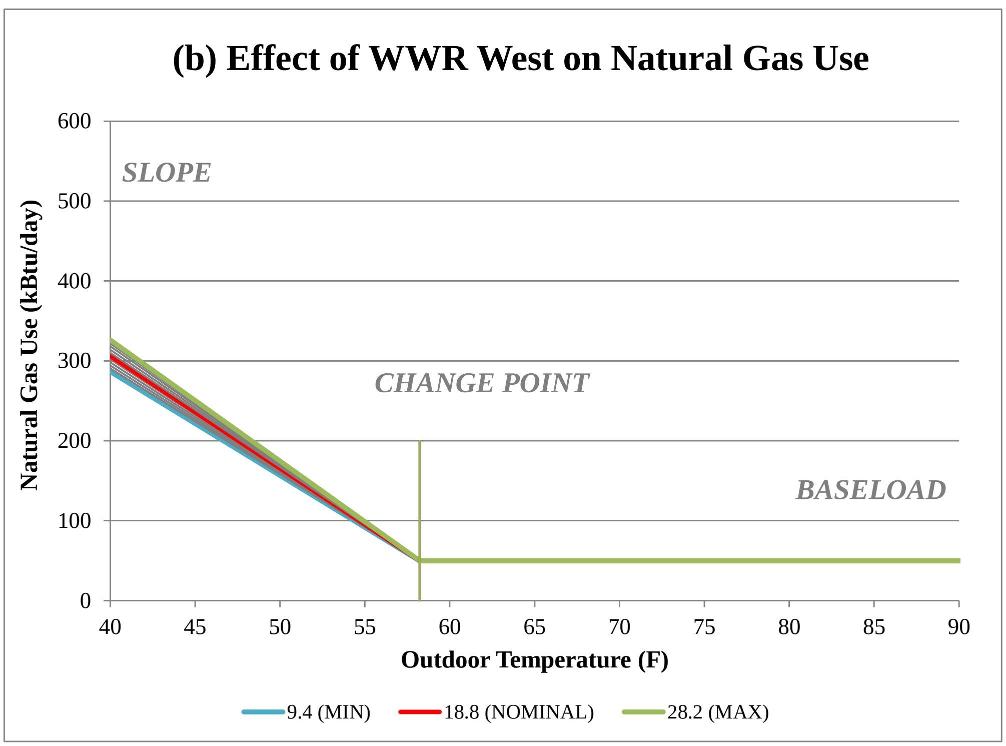
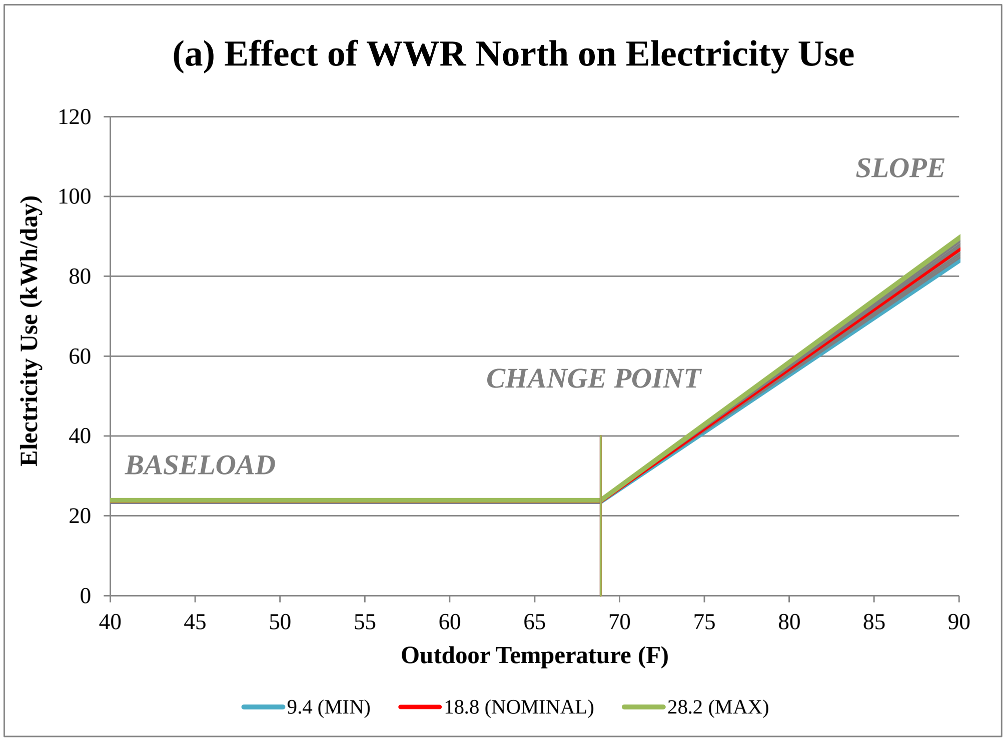


Figure 5.27 Sensitivity Test Results: Effect of WWR for West on (a) Electricity Use and (b) Natural Gas Use



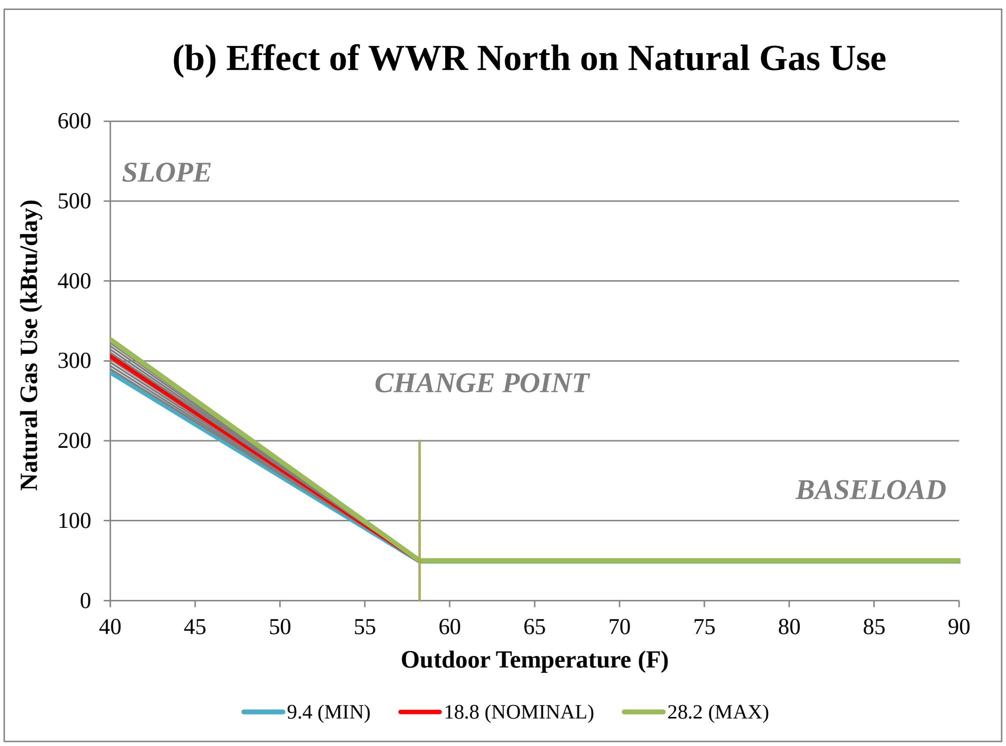


Figure 5.28 Sensitivity Test Results: Effect of WWR for North on (a) Electricity Use and (b) Natural Gas Use

coefficient for wall R-value parameter in 8th column in Table 5.4 (i.e., 0.0%) was divided by the sum of percentage ranges for 3PC change-point coefficient for all 20parameters (i.e., 8.6%). The final results for all the calculations were summarized in Table 5.5. Through the results of Table 5.5, the most influential simulation parameters for each 3P coefficient were identified. For example, the 3PC change-point coefficient was affected 20.0% by window U-value, 40.0% by SHGC and 40.0% by L&E, and 3PH change-point coefficient was affected 9.1% by wall R-value, 18.2% by window U-value, 9.1% by roof R-value, 9.1% by SHGC, 36.4% by L&E, 9.1% by AFUE and 9.1% by EF according to Table 5.5. Table 5.6 presents the most influential to the least influential parameters for each 3P coefficient. In Table 5.6 (a) through (f) shows the ranking of the influential simulation parameters by 3P coefficient. 3PC change point, baseload and slope coefficients were shown in Table 5.6 (a) through (c), respectively, and 3PH change-point, baseload and slope coefficients were shown in Table 5.6 (d) through (f), respectively. In addition, Figure 5.30 (a) through (f) presents the same results as Table 5.6 using a stacked bar graph.

Another analysis was performed to identify the most influential 3P coefficients for each simulation parameter. In order to obtain this result, the procedure described in Section 4.2.4.3 was used. The last column (i.e., the 9th column) in Table 5.4 shows the influence of each parameter on the 3PC and 3PH coefficients for each of the 20 simulation parameter when the parameter values were varied from 50% to 150% of the nominal value (equation (4.18)). For example, wall R-value changes affect the 3PC change-point coefficient by 0.0%, the 3PC baseload coefficient by 6.1%, the 3PC slope coefficient by 22.0%, the 3PH change-point coefficient by 8.9%, the 3PH baseload coefficient by 9.5%, the 3PH slope coefficient by 53.4%. Through this analysis, it was found that the wall R-value is the most influential parameter affecting the 3PH slope coefficient, and the parameter would be used to adjust 3PH slope energy use later in calibrated simulation procedure. Figure 5.29 (a) through (t) shows the influence of each parameter on the 3PC and 3PH coefficients in stacked bar graphs. Figure 5.29 (a) shows the influence of the wall R-value on the 3P coefficients, and Figure 5.29 (b) through (t) shows the influence of the parameters on the 3P coefficients for window U-value, roof R-value, wall absorption, roof absorption, shading devices, SHGC, infiltration rate, lighting & equipment, SEER, AFUE, EF, supply duct leakage and return duct leakage, supply duct R-value and return duct R-value, WWR for south, east, west and north, respectively.

Finally, through the sensitivity analyses, significant parameters for each coefficient that would be used for calibrated simulation were decided as the orange highlighted parameters in Table 5.6. These parameters were selected from the most influential parameters for each 3PC and 3PH coefficient, and were selected once more from the most of the influential 3PC and 3PH coefficients for each simulation parameter as described in the Section 4.2.5.

Table 5.4 Results of the Percentage Ranges for 3PC and 3PH Coefficients of Each Parameter

No.	Sensitivity Analysis Parameters	3PC & 3PH Coefficients		Minimum (50%)	Maximum (150%)	Nominal (100%)	% of Range from Nominal Value [%]	% of Coefficient for Each Parameter [%]
		Results of Three-parameter Change-point Regression Model						
1	Wall R-value	Elec.	Change Point (F)	68.89	68.89	68.89	0.0%	0.0%
			Base Load (kWh)	23.46	23.79	23.69	1.4%	6.1%
			Slope (kWh/F)	3.09	2.94	2.99	5.0%	22.0%
		N.G.	Change Point (F)	59.41	58.22	58.22	2.0%	8.9%
			Base Load (kBtu)	48.66	49.51	49.74	2.2%	9.5%
			Slope (kBtu/F)	-14.82	-13.11	-14.06	12.2%	53.4%
2	Window U-value	Elec.	Change Point (F)	67.71	68.89	68.89	1.7%	1.9%
			Base Load (kWh)	24.13	22.94	23.69	5.0%	5.4%
			Slope (kWh/F)	2.66	3.09	2.99	14.3%	15.5%
		N.G.	Change Point (F)	57.03	59.41	58.22	4.1%	4.4%
			Base Load (kBtu)	49.57	49.48	49.74	0.5%	0.6%
			Slope (kBtu/F)	-8.08	-17.45	-14.06	66.6%	72.2%
3	Roof R-value	Elec.	Change Point (F)	68.89	68.89	68.89	0.0%	0.0%
			Base Load (kWh)	24.13	23.58	23.69	2.3%	4.6%
			Slope (kWh/F)	3.30	2.86	2.99	14.8%	29.2%
		N.G.	Change Point (F)	59.41	58.22	58.22	2.0%	4.0%
			Base Load (kBtu)	49.73	49.31	49.74	0.9%	1.7%
			Slope (kBtu/F)	-16.53	-12.24	-14.06	30.5%	60.4%
4	Wall Absorption	Elec.	Change Point (F)	68.89	68.89	68.89	0.0%	0.0%
			Base Load (kWh)	23.25	24.14	23.69	3.8%	17.3%
			Slope (kWh/F)	2.89	3.09	2.99	6.7%	30.5%
		N.G.	Change Point (F)	58.22	58.22	58.22	0.0%	0.0%
			Base Load (kBtu)	50.07	49.51	49.74	1.1%	5.2%
			Slope (kBtu/F)	-14.82	-13.37	-14.06	10.3%	47.1%
5	Roof Absorption	Elec.	Change Point (F)	68.89	68.89	68.89	0.0%	0.0%
			Base Load (kWh)	22.71	23.86	23.27	4.9%	15.2%
			Slope (kWh/F)	2.52	3.07	2.78	19.8%	61.5%
		N.G.	Change Point (F)	58.22	58.22	58.22	0.0%	0.0%
			Base Load (kBtu)	49.92	49.73	49.81	0.4%	1.2%
			Slope (kBtu/F)	-14.97	-13.94	-14.42	7.1%	22.1%
6	Shading Devices	Elec.	Change Point (F)	68.89	68.89	68.89	0.0%	0.0%
			Base Load (kWh)	25.42	22.76	23.69	11.2%	28.4%
			Slope (kWh/F)	3.16	2.90	2.99	8.7%	22.0%
		N.G.	Change Point (F)	58.22	58.22	58.22	0.0%	0.0%
			Base Load (kBtu)	49.62	49.94	49.74	0.7%	1.7%
			Slope (kBtu/F)	-12.61	-15.28	-14.06	19.0%	48.0%
7	Solar Heat Gain Coefficient (SHGC)	Elec.	Change Point (F)	70.08	67.71	68.89	3.4%	7.1%
			Base Load (kWh)	22.74	24.93	23.69	9.2%	19.2%
			Slope (kWh/F)	2.90	3.03	2.99	4.2%	8.8%
		N.G.	Change Point (F)	59.41	58.22	58.22	2.0%	4.2%
			Base Load (kBtu)	49.09	49.32	49.74	1.3%	2.7%
			Slope (kBtu/F)	-15.56	-11.63	-14.06	27.9%	58.0%

Table 5.4 Continued

		Results of Three-parameter Change-point Regression Model						
No.	**Sensitivity Analysis Parameters**	**3PC & 3PH Coefficients**		**Minimum (50%)**	**Maximum (150%)**	**Nominal (100%)**	**% of Range from Nominal Value [%]**	**% of Coefficient for Each Parameter [%]**
8	**Infiltration Rate**	**Elec.**	**Change Point (F)**	68.89	68.89	68.89	0.0%	0.0%
			Base Load (kWh)	23.96	23.45	23.69	2.2%	4.1%
			Slope (kWh/F)	2.86	3.11	2.99	8.7%	16.3%
		N.G.	**Change Point (F)**	58.22	58.22	58.22	0.0%	0.0%
			Base Load (kBtu)	49.51	50.23	49.74	1.5%	2.7%
			Slope (kBtu/F)	-11.23	-16.99	-14.06	41.0%	76.9%
9	**Lighting & Equipment**	**Elec.**	**Change Point (F)**	70.08	67.71	68.89	3.4%	2.5%
			Base Load (kWh)	12.59	35.05	23.69	94.8%	67.9%
			Slope (kWh/F)	2.85	3.09	2.99	8.0%	5.7%
		N.G.	**Change Point (F)**	60.59	55.85	58.22	8.1%	5.8%
			Base Load (kBtu)	49.21	50.22	49.74	2.0%	1.4%
			Slope (kBtu/F)	-15.46	-12.20	-14.06	23.2%	16.6%
10	**Cooling System Efficiency (SEER)**	**Elec.**	**Change Point (F)**	68.89	68.89	68.89	0.0%	0.0%
			Base Load (kWh)	25.35	22.95	23.69	10.1%	7.8%
			Slope (kWh/F)	5.57	2.00	2.99	119.2%	91.4%
		N.G.	**Change Point (F)**	58.22	58.22	58.22	0.0%	0.0%
			Base Load (kBtu)	49.74	49.74	49.74	0.0%	0.0%
			Slope (kBtu/F)	-14.06	-14.21	-14.06	1.0%	0.8%
11	**Heating System Efficiency (AFUE)**	**Elec.**	**Change Point (F)**	68.89	68.89	68.89	0.0%	0.0%
			Base Load (kWh)	23.69	23.69	23.69	0.0%	0.0%
			Slope (kWh/F)	2.99	2.99	2.99	0.0%	0.0%
		N.G.	**Change Point (F)**	58.22	59.41	58.22	2.0%	1.5%
			Base Load (kBtu)	49.70	48.76	49.74	2.0%	1.5%
			Slope (kBtu/F)	-27.27	-8.79	-14.06	131.4%	97.0%
12	**Hot Water Heater Efficiency (EF)**	**Elec.**	**Change Point (F)**	68.89	68.89	68.89	0.0%	0.0%
			Base Load (kWh)	23.69	23.69	23.69	0.0%	0.0%
			Slope (kWh/F)	2.99	2.99	2.99	0.0%	0.0%
		N.G.	**Change Point (F)**	59.41	58.22	58.22	2.0%	1.4%
			Base Load (kBtu)	101.86	33.31	50.02	137.1%	96.6%
			Slope (kBtu/F)	-13.68	-13.78	-14.07	2.8%	2.0%
13	**Supply Duct Leakage**	**Elec.**	**Change Point (F)**	68.89	68.89	68.89	0.0%	0.0%
			Base Load (kWh)	23.56	23.84	23.69	1.2%	5.7%
			Slope (kWh/F)	2.85	3.15	2.99	10.0%	47.8%
		N.G.	**Change Point (F)**	58.22	58.22	58.22	0.0%	0.0%
			Base Load (kBtu)	49.77	49.72	49.74	0.1%	0.5%
			Slope (kBtu/F)	-13.43	-14.78	-14.06	9.6%	46.0%
14	**Return Duct Leakage**	**Elec.**	**Change Point (F)**	68.89	68.89	68.89	0.0%	0.0%
			Base Load (kWh)	23.87	23.35	23.69	2.2%	5.6%
			Slope (kWh/F)	2.65	3.46	2.99	27.2%	69.5%
		N.G.	**Change Point (F)**	58.22	58.22	58.22	0.0%	0.0%
			Base Load (kBtu)	49.83	49.65	49.74	0.4%	0.9%
			Slope (kBtu/F)	-13.45	-14.76	-14.06	9.4%	23.9%

Table 5.4 Continued

		Results of Three-parameter Change-point Regression Model						
No.	**Sensitivity Analysis Parameters**	**3PC & 3PH Coefficients**		**Minimum (50%)**	**Maximum (150%)**	**Nominal (100%)**	**% of Range from Nominal Value [%]**	**% of Coefficient for Each Parameter [%]**
15	**Supply Duct R-value**	**Elec.**	**Change Point (F)**	68.89	68.89	68.89	0.0%	0.0%
			Base Load (kWh)	23.68	23.69	23.69	0.0%	0.2%
			Slope (kWh/F)	3.35	2.89	2.99	15.4%	56.6%
		N.G.	**Change Point (F)**	58.22	58.22	58.22	0.0%	0.0%
			Base Load (kBtu)	49.63	49.78	49.74	0.3%	1.1%
			Slope (kBtu/F)	-15.30	-13.69	-14.06	11.4%	42.1%
16	**Return Duct R-value**	**Elec.**	**Change Point (F)**	68.89	68.89	68.89	0.0%	0.0%
			Base Load (kWh)	23.66	23.70	23.69	0.1%	2.8%
			Slope (kWh/F)	3.06	2.97	2.99	3.1%	60.1%
		N.G.	**Change Point (F)**	58.22	58.22	58.22	0.0%	0.0%
			Base Load (kBtu)	49.72	49.75	49.74	0.1%	1.4%
			Slope (kBtu/F)	-14.26	-14.00	-14.06	1.8%	35.7%
17	**WWR South**	**Elec.**	**Change Point (F)**	68.89	68.89	68.89	0.0%	0.0%
			Base Load (kWh)	23.05	24.43	23.69	5.8%	38.1%
			Slope (kWh/F)	2.92	3.05	2.99	4.5%	29.7%
		N.G.	**Change Point (F)**	58.22	58.22	58.22	0.0%	0.0%
			Base Load (kBtu)	49.74	49.87	49.74	0.3%	1.7%
			Slope (kBtu/F)	-13.82	-14.47	-14.06	4.6%	30.5%
18	**WWR East**	**Elec.**	**Change Point (F)**	68.89	68.89	68.89	0.0%	0.0%
			Base Load (kWh)	23.22	24.17	23.69	4.0%	21.1%
			Slope (kWh/F)	2.88	3.09	2.99	6.9%	36.2%
		N.G.	**Change Point (F)**	58.22	58.22	58.22	0.0%	0.0%
			Base Load (kBtu)	49.59	49.96	49.74	0.7%	4.0%
			Slope (kBtu/F)	-13.60	-14.63	-14.06	7.3%	38.7%
19	**WWR West**	**Elec.**	**Change Point (F)**	68.89	68.89	68.89	0.0%	0.0%
			Base Load (kWh)	23.57	23.82	23.69	1.1%	4.5%
			Slope (kWh/F)	2.88	3.09	2.99	6.9%	28.5%
		N.G.	**Change Point (F)**	58.22	58.22	58.22	0.0%	0.0%
			Base Load (kBtu)	49.52	50.03	49.74	1.0%	4.3%
			Slope (kBtu/F)	-13.01	-15.15	-14.06	15.2%	62.8%
20	**WWR North**	**Elec.**	**Change Point (F)**	68.89	68.89	68.89	0.0%	0.0%
			Base Load (kWh)	23.54	23.85	23.69	1.3%	4.9%
			Slope (kWh/F)	2.86	3.11	2.99	8.4%	31.8%
		N.G.	**Change Point (F)**	58.22	58.22	58.22	0.0%	0.0%
			Base Load (kBtu)	49.50	50.05	49.74	1.1%	4.2%
			Slope (kBtu/F)	-12.98	-15.18	-14.06	15.7%	59.1%

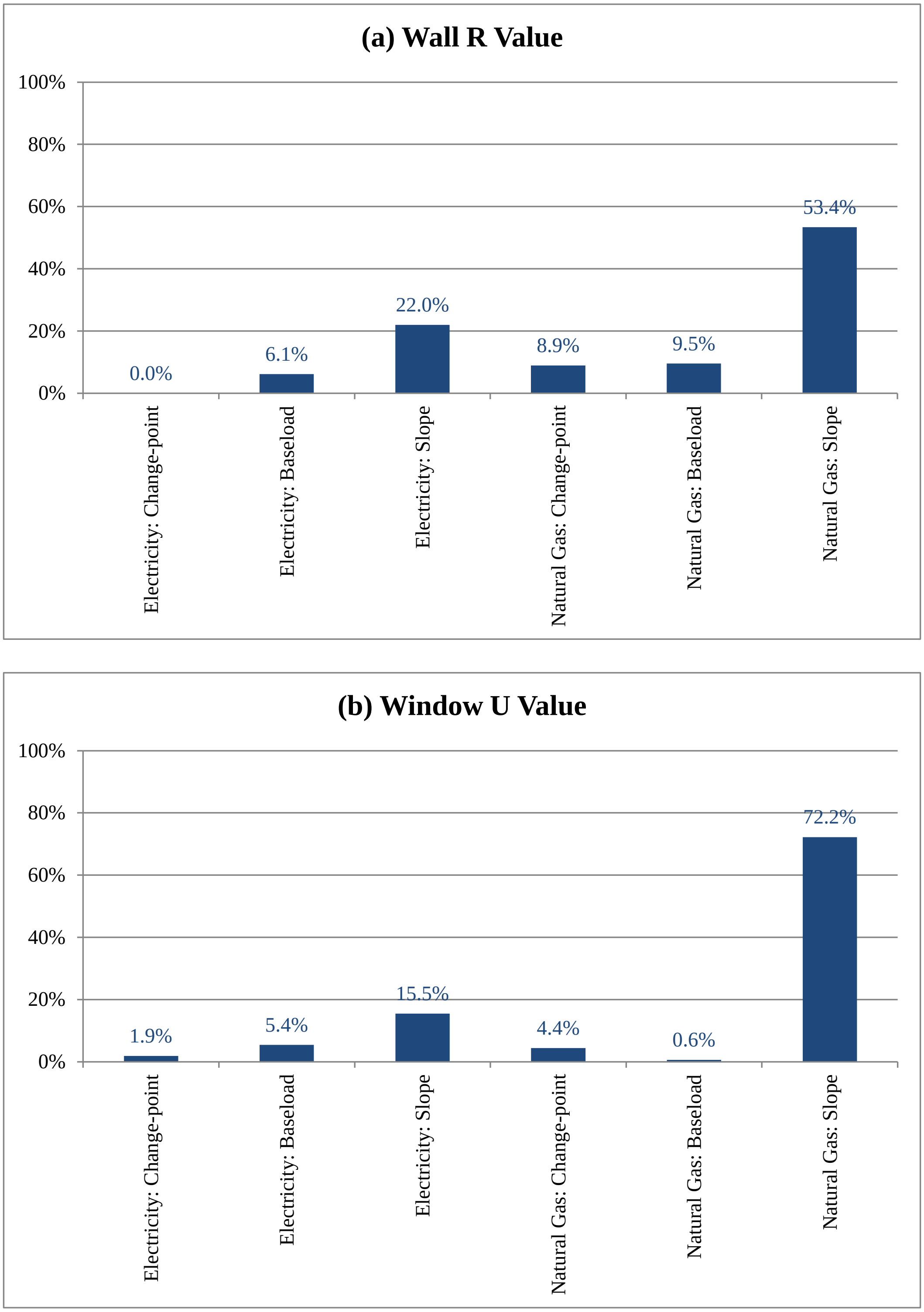
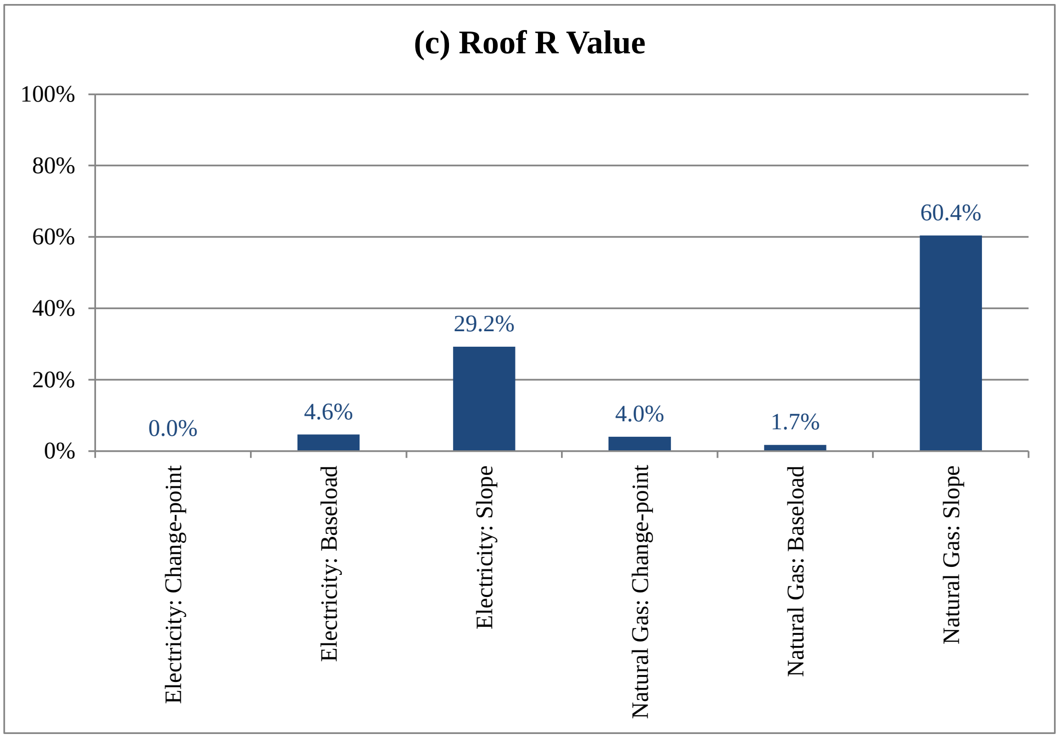


Figure 5.29 Percentage of 3PC and 3PH Coefficients for Parameters



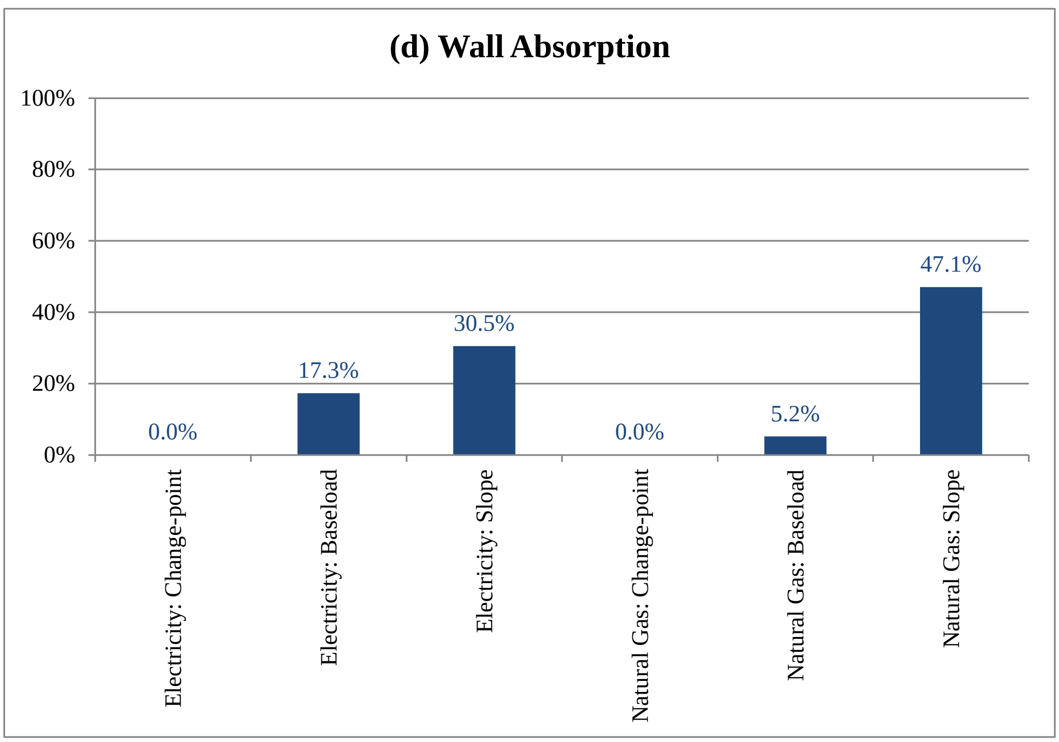
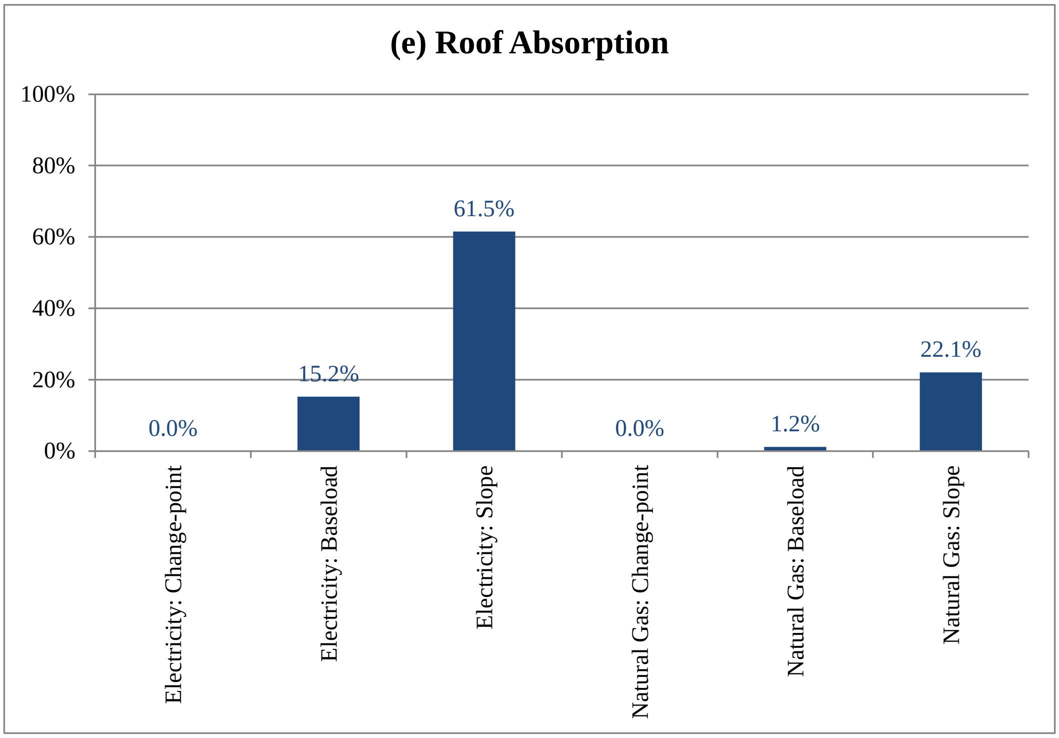


Figure 5.29 Continued



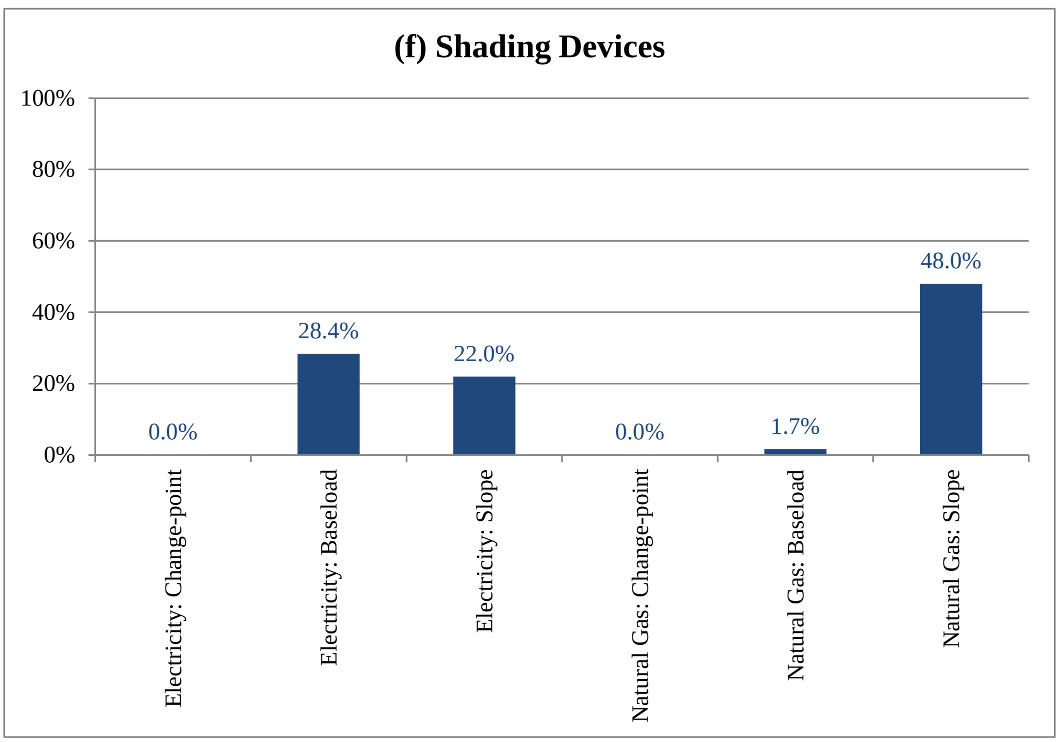
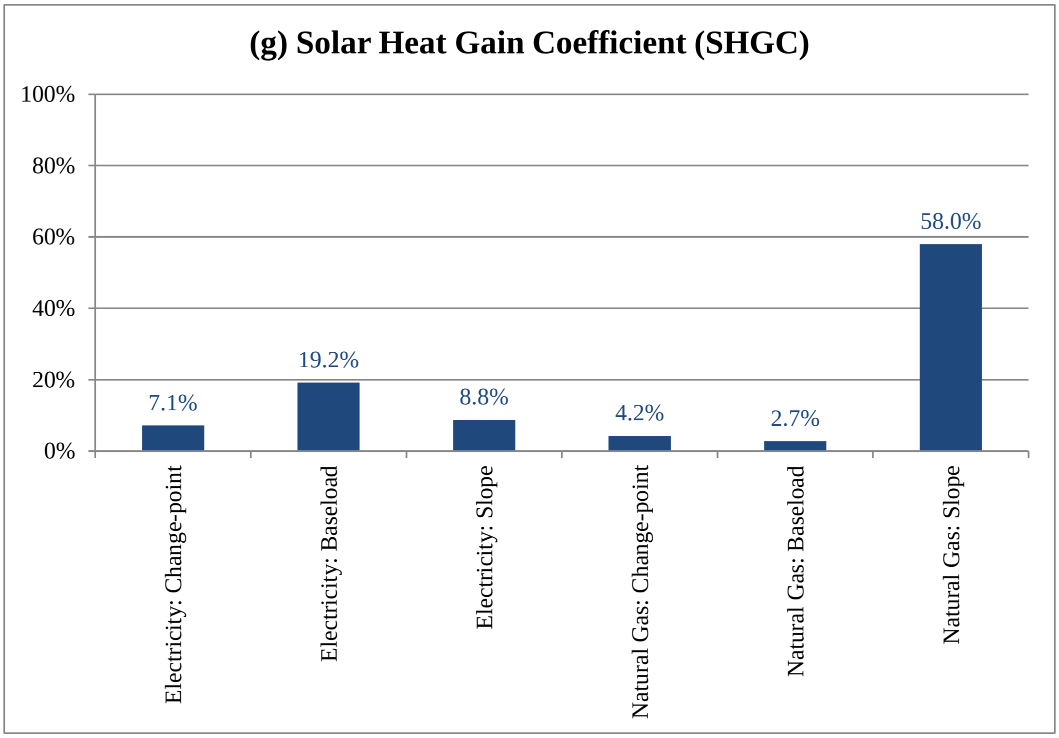


Figure 5.29 Continued



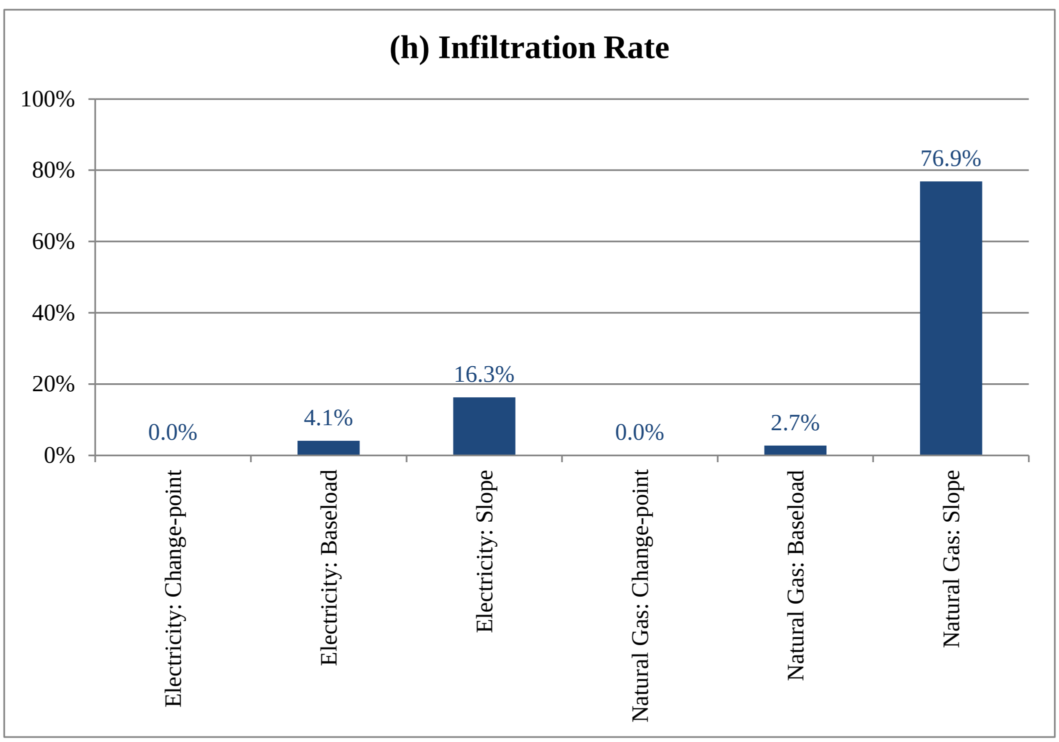
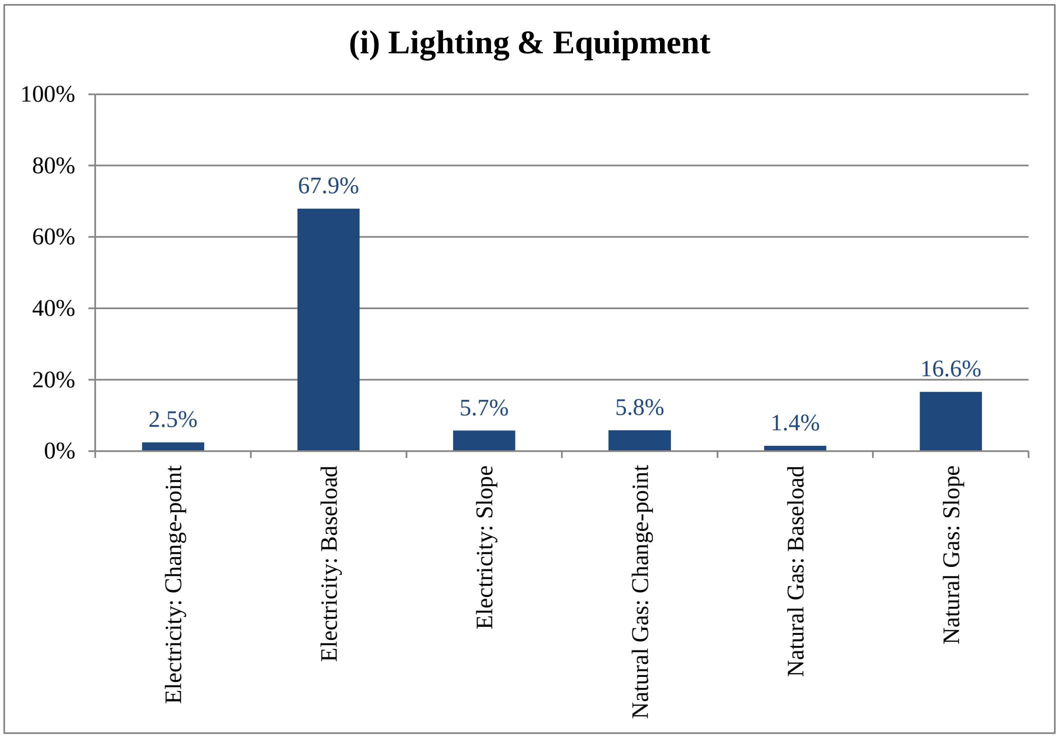


Figure 5.29 Continued



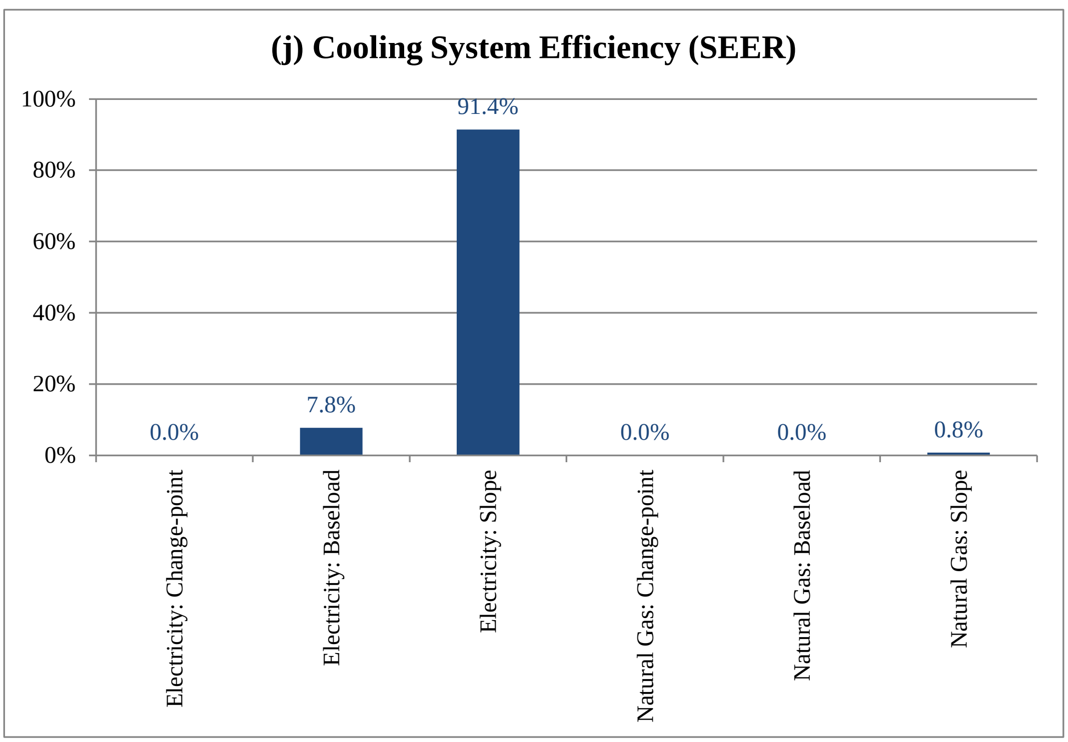
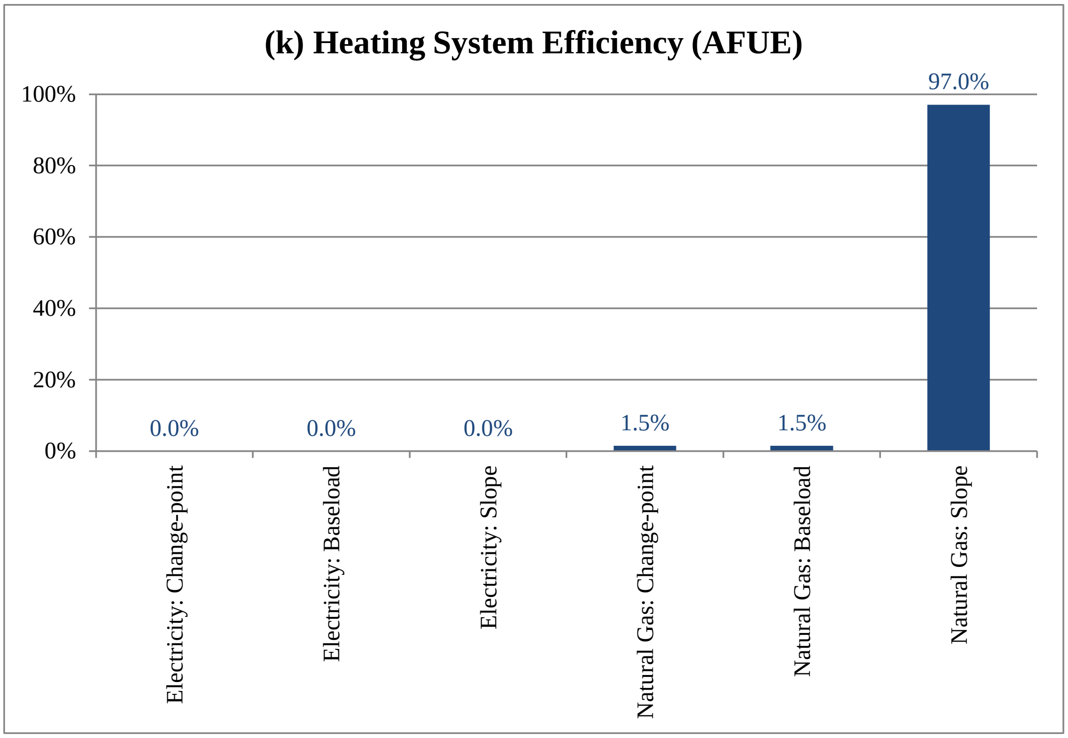
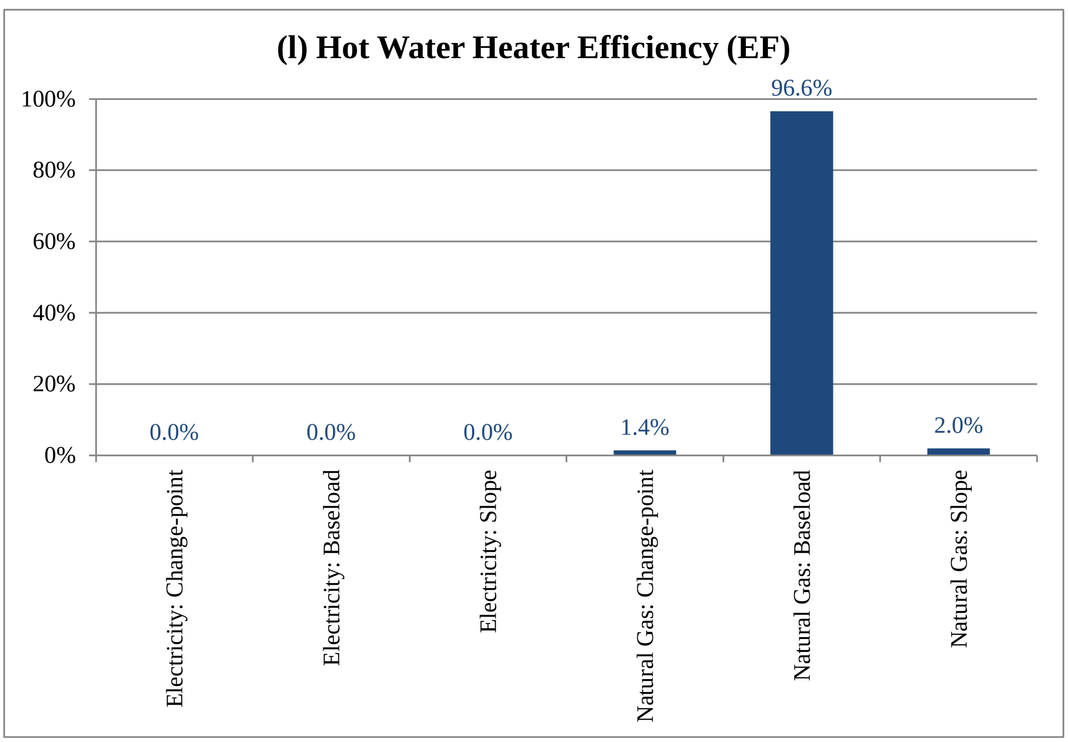


Figure 5.29   Continued





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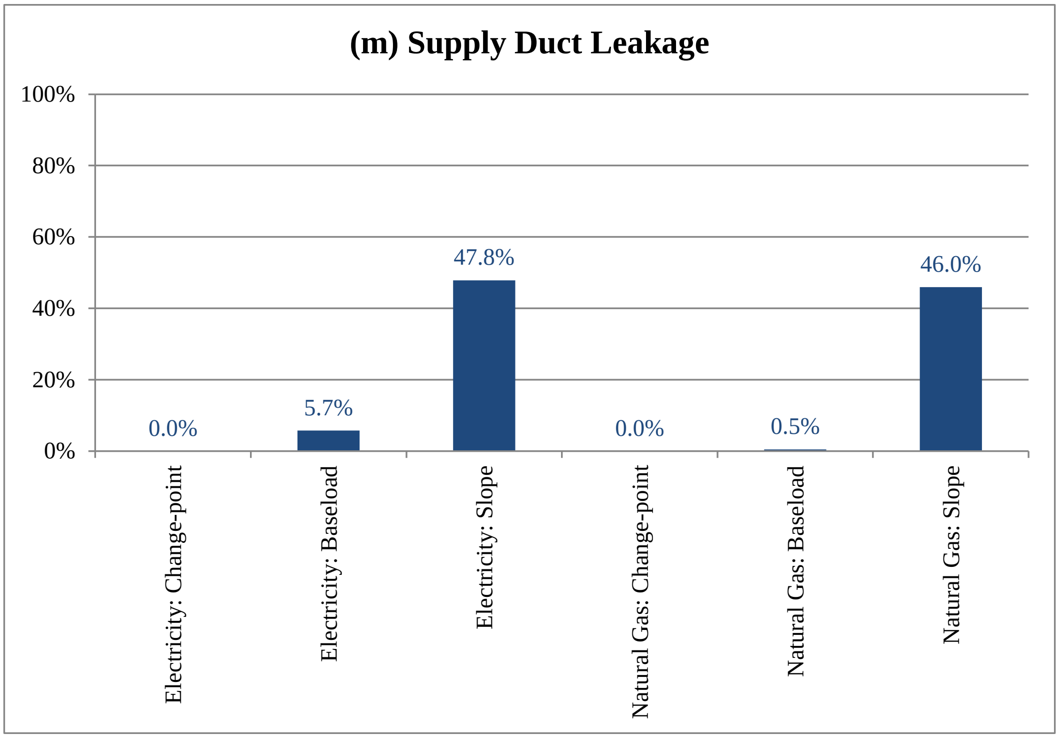

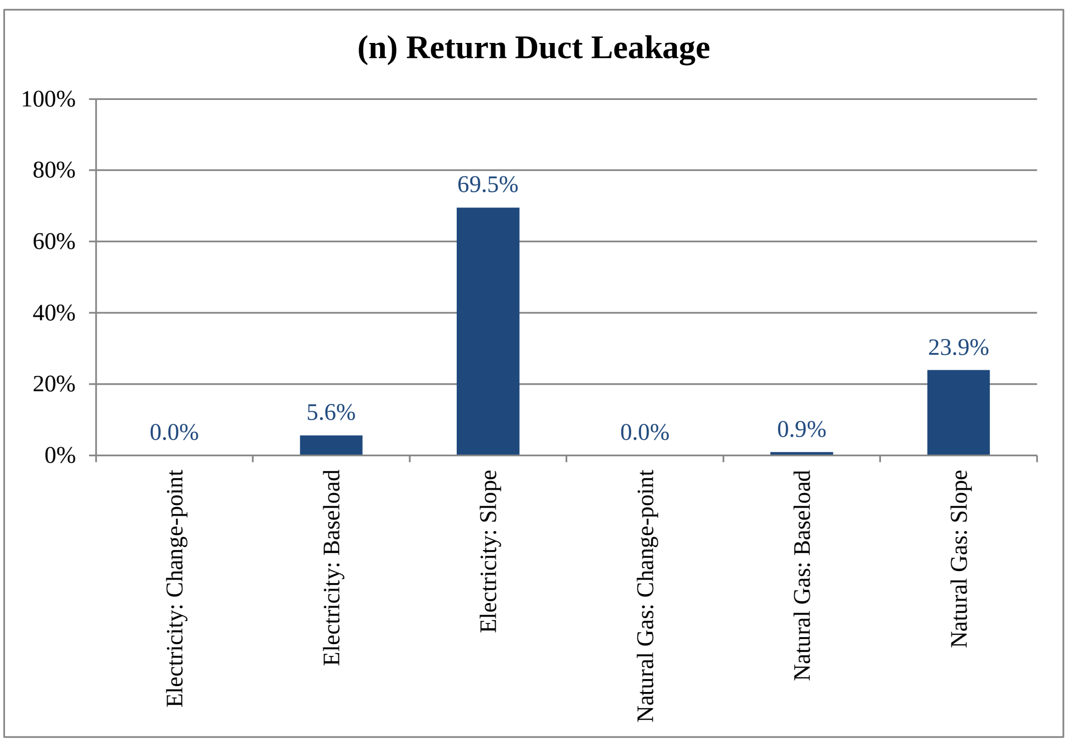

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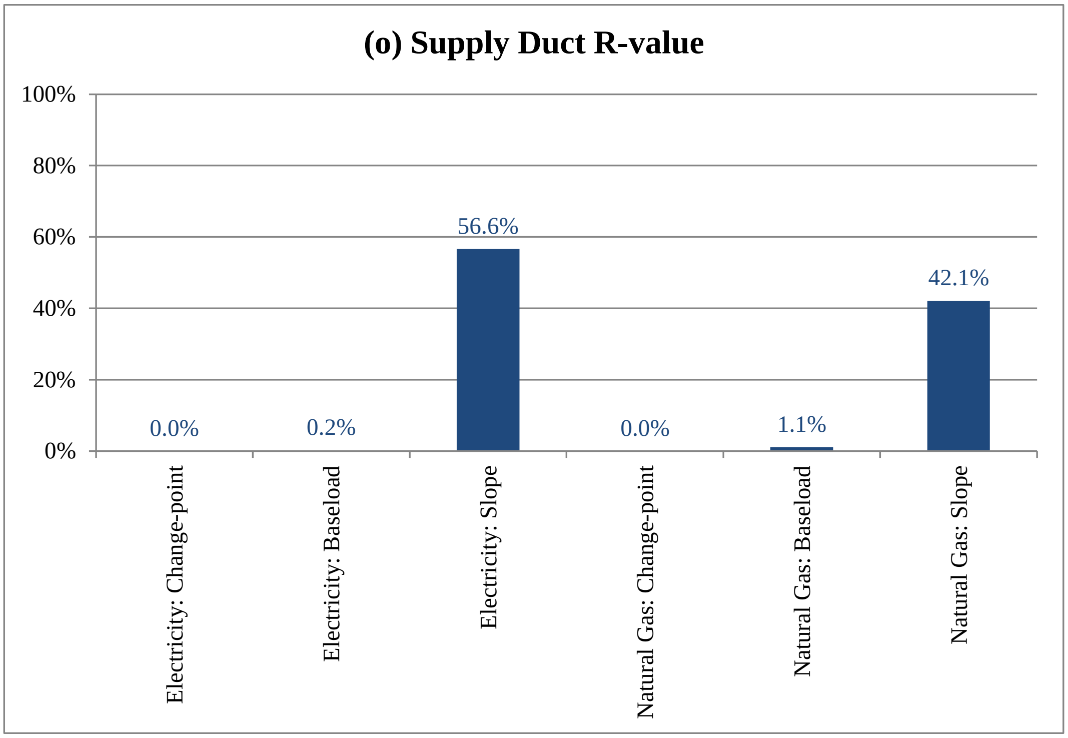

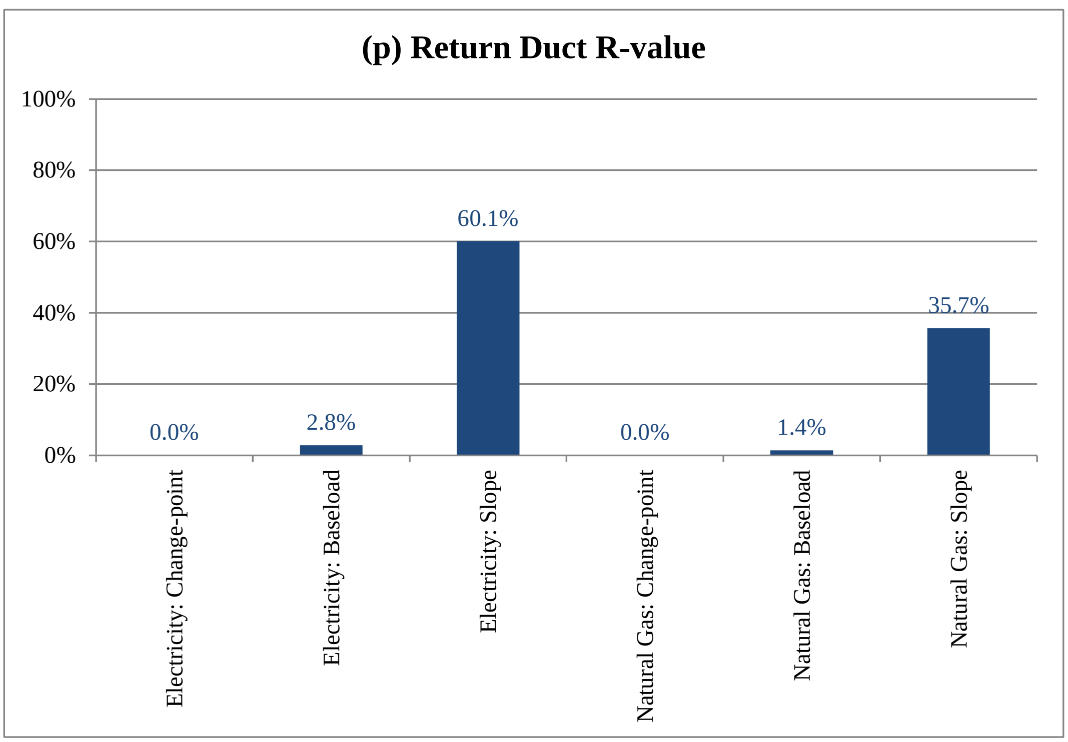

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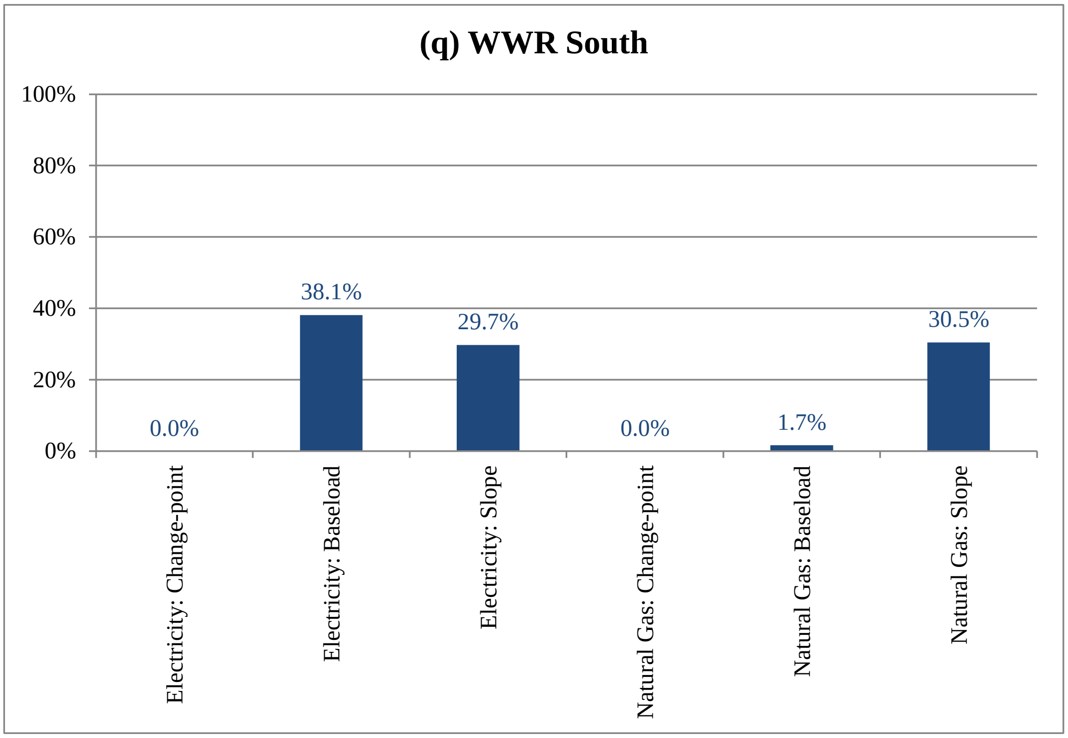

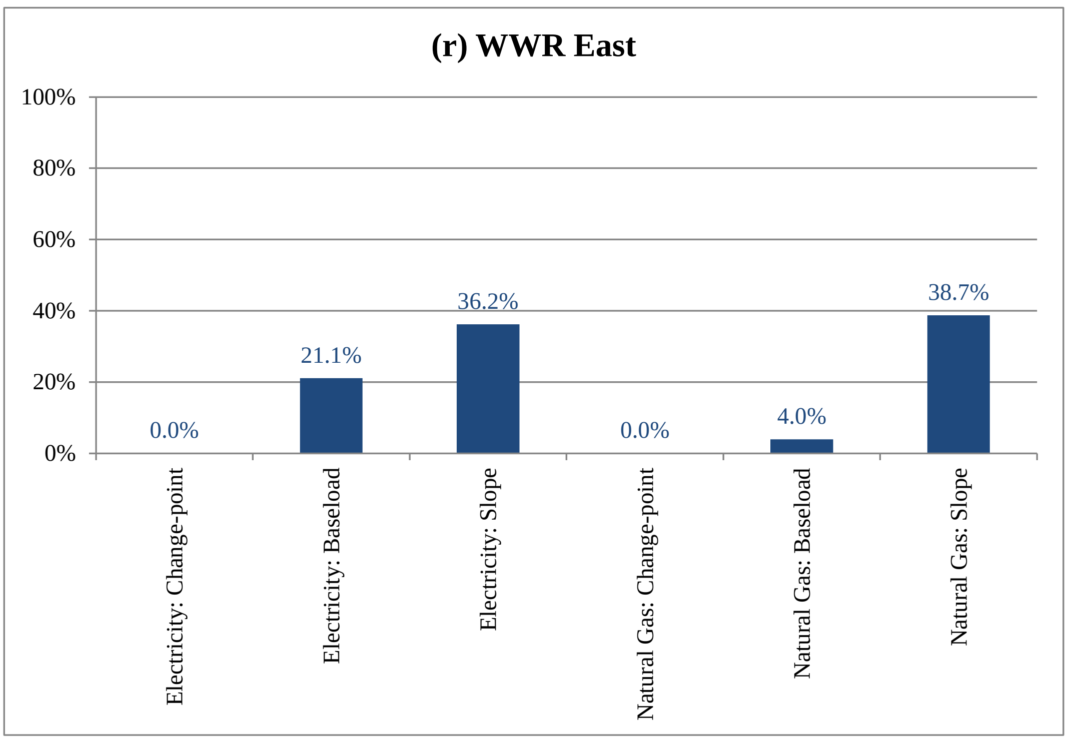

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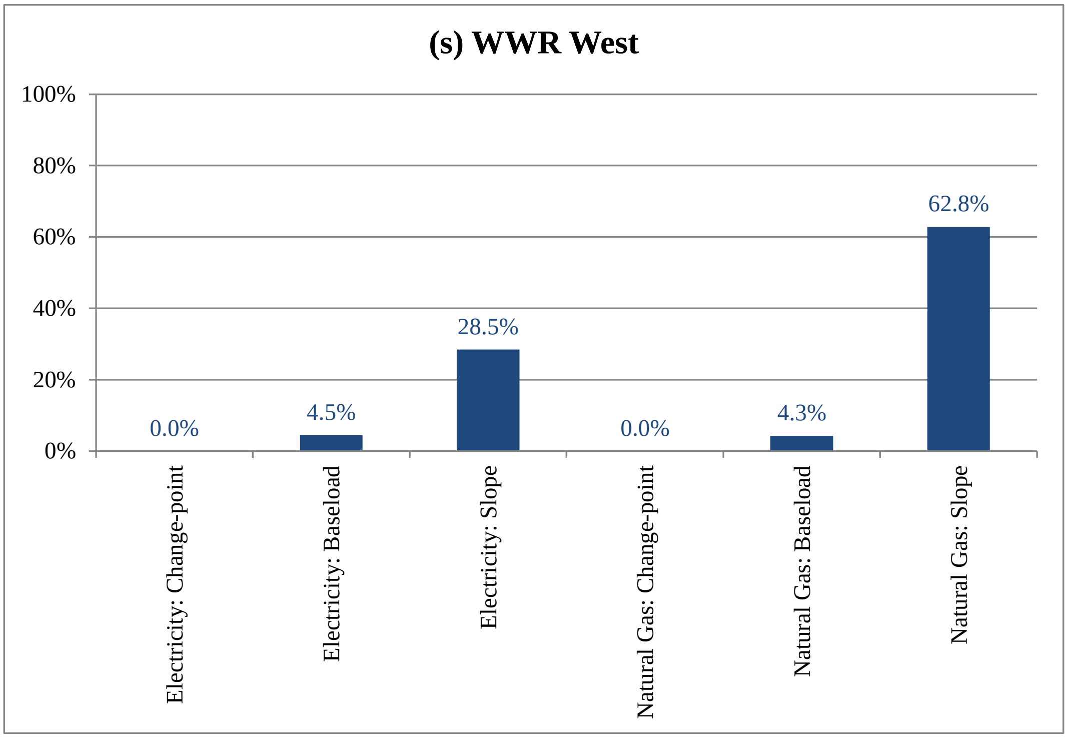


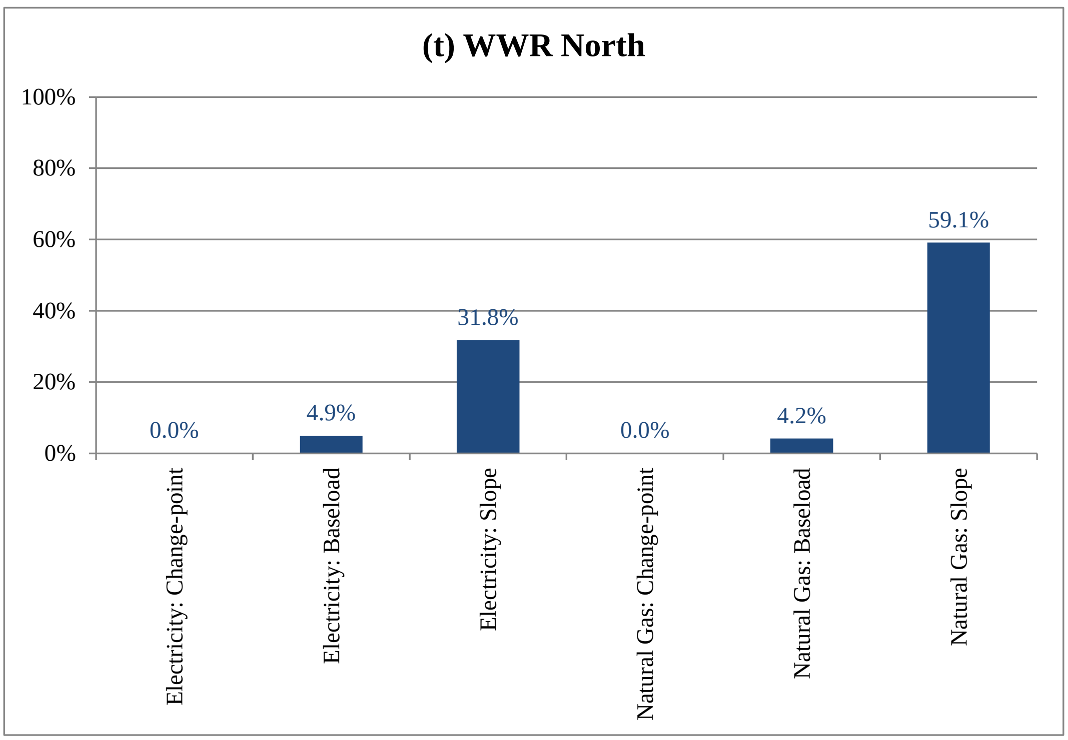


Figure 5.29 Continued

Table 5.5 Results of the Percentage of 3PC and 3PH Coefficients for Simulation Parameters

	Electricity Use (3PC)			Natural Gas Use (3PH)		
	Change Point [F]	**Base Load [kWh]**	**Slope [kWh/F]**	**Change Point [F]**	**Base Load [kBtu]**	**Slope [kBtu/F]**
Wall R-value	0.0%	0.9%	1.7%	9.1%	1.4%	2.7%
Window U-value	20.0%	3.1%	4.9%	18.2%	0.4%	14.9%
Roof R-value	0.0%	1.4%	5.1%	9.1%	0.6%	6.8%
Wall Absorption	0.0%	2.3%	2.3%	0.0%	0.7%	2.3%
Roof Absorption	0.0%	3.1%	6.8%	0.0%	0.2%	1.6%
Shading Devices	0.0%	7.0%	3.0%	0.0%	0.4%	4.2%
SHGC	40.0%	5.7%	1.4%	9.1%	0.9%	6.2%
Infiltration Rate	0.0%	1.4%	3.0%	0.0%	0.9%	9.1%
L&E	40.0%	59.0%	2.7%	36.4%	1.3%	5.2%
SEER	0.0%	6.3%	40.9%	0.0%	0.0%	0.2%
AFUE	0.0%	0.0%	0.0%	9.1%	1.3%	29.3%
EF	0.0%	0.0%	0.0%	9.1%	89.3%	0.6%
Supply Duct Leakage	0.0%	0.7%	3.4%	0.0%	0.1%	2.2%
Return Duct Leakage	0.0%	1.4%	9.3%	0.0%	0.2%	2.1%
Supply Duct R-value	0.0%	0.0%	5.3%	0.0%	0.2%	2.6%
Return Duct R-value	0.0%	0.1%	1.1%	0.0%	0.0%	0.4%
WWR South	0.0%	3.6%	1.5%	0.0%	0.2%	1.0%
WWR East	0.0%	2.5%	2.4%	0.0%	0.5%	1.6%
WWR West	0.0%	0.7%	2.4%	0.0%	0.7%	3.4%
WWR North	0.0%	0.8%	2.9%	0.0%	0.7%	3.5%
TOTAL	100%	100%	100%	100%	100%	100%

Table 5.6 Most Influential Parameters for 3PC and 3PH Coefficients

(a) Electricity: Change Point [%]

Parameter	%	Accumulated %
L&E	40.00%	40.00%
SHGC	40.00%	80.00%
Window U-value	20.00%	100.00%
Wall R-value	0.00%	100.00%
Roof R-value	0.00%	100.00%
Wall Absorption	0.00%	100.00%
Roof Absorption	0.00%	100.00%
Shading Devices	0.00%	100.00%
Infiltration Rate	0.00%	100.00%
SEER	0.00%	100.00%
AFUE	0.00%	100.00%
EF	0.00%	100.00%
Supply Duct Leakage	0.00%	100.00%
Return Duct Leakage	0.00%	100.00%
Supply Duct R-value	0.00%	100.00%
Return Duct R-value	0.00%	100.00%
WWR South	0.00%	100.00%
WWR East	0.00%	100.00%
WWR West	0.00%	100.00%
WWR North	0.00%	100.00%

(b) Electricity: Base Load [%]

Parameter	%	Accumulated %
L&E	58.98%	58.98%
Shading Devices	6.98%	65.96%
SEER	6.30%	72.26%
SHGC	5.74%	78.00%
WWR South	3.60%	81.60%
Window U-value	3.12%	84.72%
Roof Absorption	3.06%	87.78%
WWR East	2.49%	90.27%
Wall Absorption	2.35%	92.62%
Roof R-value	1.45%	94.07%
Return Duct Leakage	1.36%	95.43%
Infiltration Rate	1.35%	96.78%
Wall R-value	0.87%	97.65%
WWR North	0.81%	98.46%
Supply Duct Leakage	0.75%	99.21%
WWR West	0.67%	99.88%
Return Duct R-value	0.09%	99.97%
Supply Duct R-value	0.03%	100.00%
AFUE	0.00%	100.00%
EF	0.00%	100.00%

(c) Electricity: Slope [%]

Parameter	%	Accumulated %
SEER	40.86%	40.86%
Return Duct Leakage	9.32%	50.18%
Roof Absorption	6.80%	56.98%
Supply Duct R-value	5.28%	62.26%
Roof R-value	5.06%	67.32%
Window U-value	4.91%	72.23%
Supply Duct Leakage	3.44%	75.67%
Shading Devices	2.98%	78.65%
Infiltration Rate	2.97%	81.62%
WWR North	2.89%	84.51%
L&E	2.74%	87.25%
WWR West	2.36%	89.61%
WWR East	2.35%	91.96%
Wall Absorption	2.28%	94.24%
Wall R-value	1.72%	95.96%
WWR South	1.55%	97.51%
SHGC	1.45%	98.96%
Return Duct R-value	1.05%	100.01%
AFUE	0.00%	100.01%
EF	0.00%	100.01%

Table 5.6 Continued

(d) Natural Gas: Change Point [%]

Parameter	%	Accumulated %
L&E	36.36%	36.36%
Window U-value	18.18%	54.54%
Wall R-value	9.09%	63.63%
Roof R-value	9.09%	72.72%
SHGC	9.09%	81.81%
AFUE	9.09%	90.90%
EF	9.09%	99.99%
Wall Absorption	0.00%	99.99%
Roof Absorption	0.00%	99.99%
Shading Devices	0.00%	99.99%
Infiltration Rate	0.00%	99.99%
SEER	0.00%	99.99%
Supply Duct Leakage	0.00%	99.99%
Return Duct Leakage	0.00%	99.99%
Supply Duct R-value	0.00%	99.99%
Return Duct R-value	0.00%	99.99%
WWR South	0.00%	99.99%
WWR East	0.00%	99.99%
WWR West	0.00%	99.99%
WWR North	0.00%	99.99%

(e) Natural Gas: Base Load [%]

Parameter	%	Accumulated %
EF	89.25%	89.25%
Wall R-value	1.42%	90.67%
L&E	1.32%	91.99%
AFUE	1.29%	93.28%
Infiltration Rate	0.95%	94.23%
SHGC	0.85%	95.08%
Wall Absorption	0.73%	95.81%
WWR North	0.72%	96.53%
WWR West	0.67%	97.20%
Roof R-value	0.56%	97.76%
WWR East	0.49%	98.25%
Shading Devices	0.43%	98.68%
Window U-value	0.35%	99.03%
Roof Absorption	0.25%	99.28%
Return Duct Leakage	0.24%	99.52%
Supply Duct R-value	0.20%	99.72%
WWR South	0.16%	99.88%
Supply Duct Leakage	0.06%	99.94%
Return Duct R-value	0.05%	99.99%
SEER	0.01%	100.00%

(f) Natural Gas: Slope [%]

Parameter	%	Accumulated %
AFUE	29.30%	29.30%
Window U-value	14.90%	44.20%
Infiltration Rate	9.10%	53.30%
Roof R-value	6.80%	60.10%
SHGC	6.20%	66.30%
L&E	5.20%	71.50%
Shading Devices	4.20%	75.70%
WWR North	3.50%	79.20%
WWR West	3.40%	82.60%
Wall R-value	2.70%	85.30%
Supply Duct R-value	2.60%	87.90%
Wall Absorption	2.30%	90.20%
Supply Duct Leakage	2.20%	92.40%
Return Duct Leakage	2.10%	94.50%
WWR East	1.60%	96.10%
Roof Absorption	1.60%	97.70%
WWR South	1.00%	98.70%
EF	0.60%	99.30%
Return Duct R-value	0.40%	99.70%
SEER	0.20%	99.90%

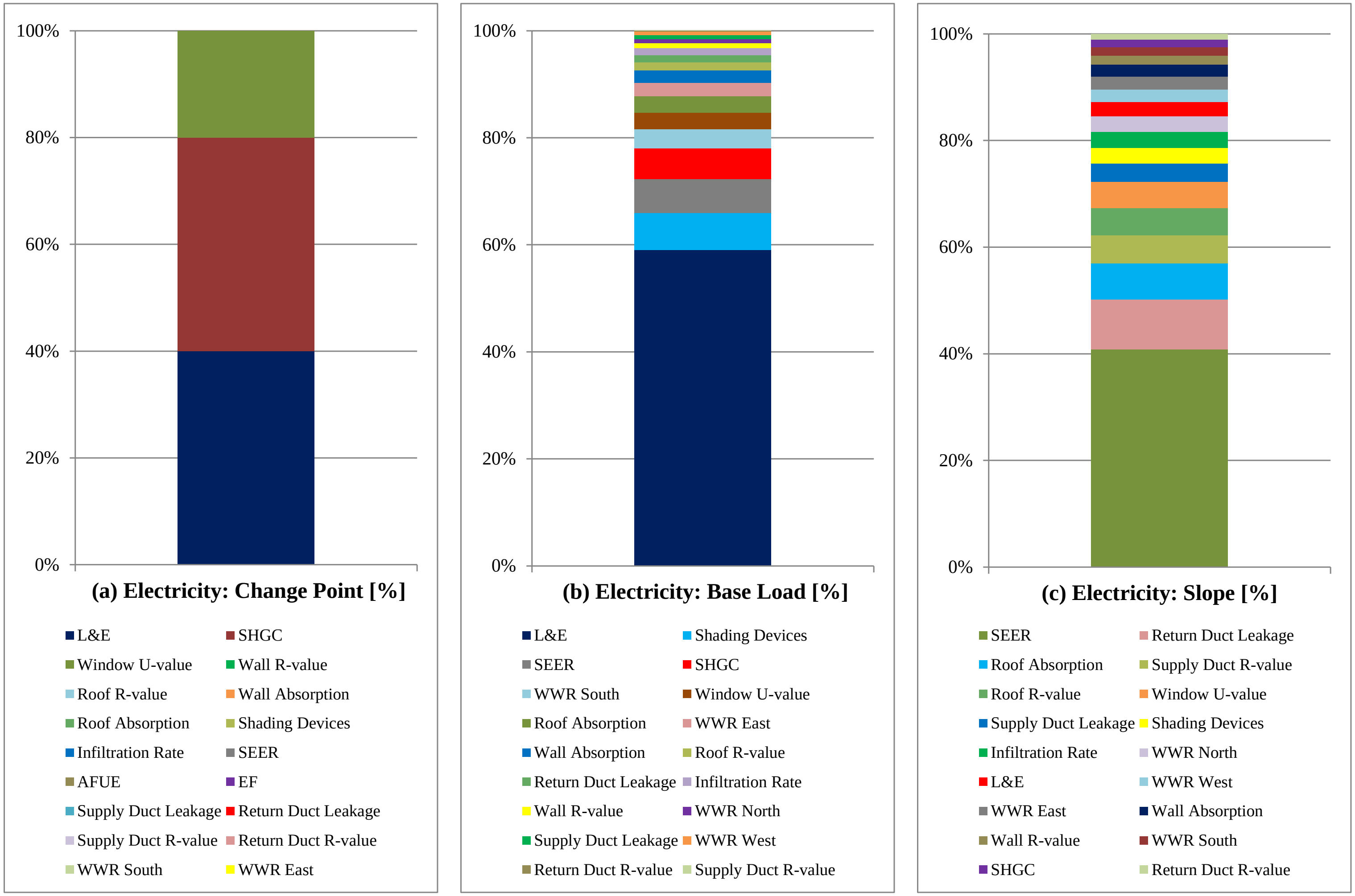


Figure 5.30 Percentages of 3PC and 3PH Coefficients for Simulation Parameters

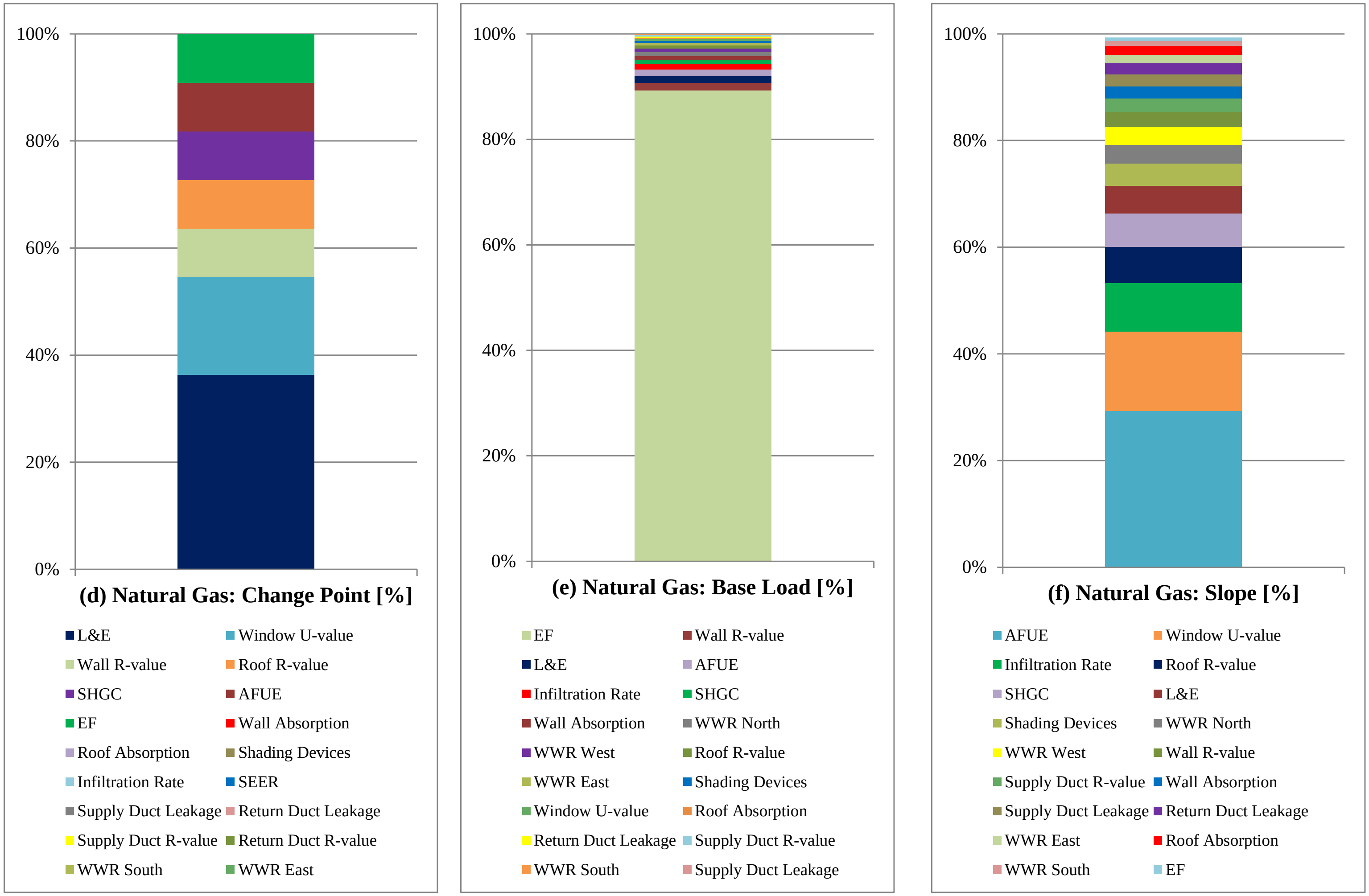
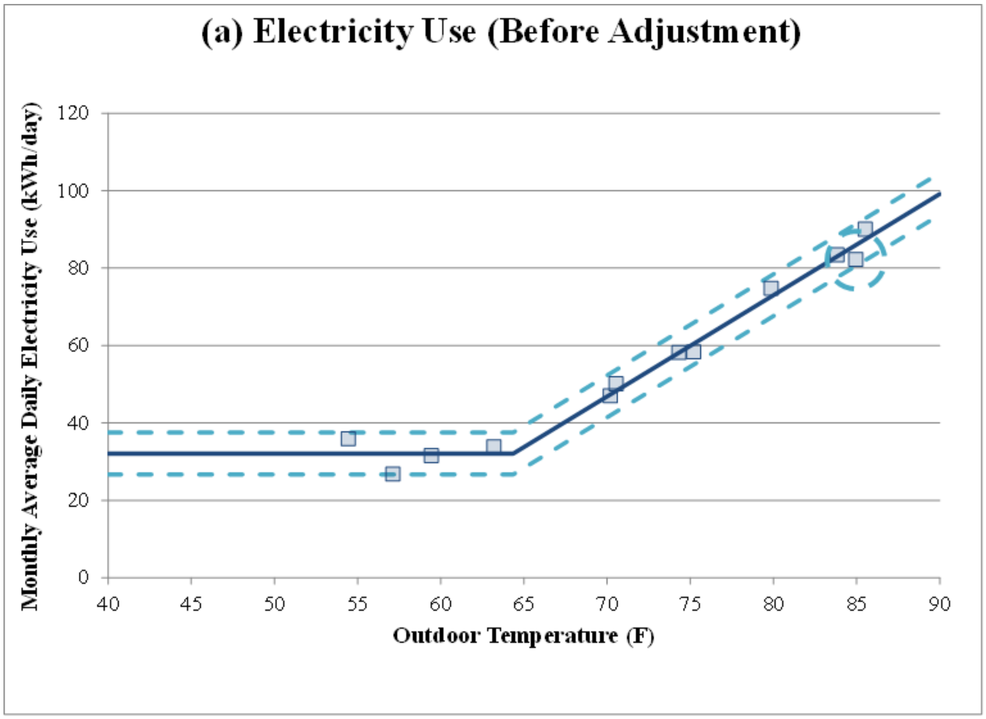


Figure 5.30 Continued

5.1.4 Results of Calibration for As-built Case-study House #1 Simulation

The as-built case-study house #1 simulation was calibrated using the actual electricity and natural gas utility bills and the coincident weather data. Before starting the calibration, utility billing data was inspected for abnormal energy use, taking into account weather conditions. Abnormal data was extracted to avoid inaccurate calibration as described in Section 4.2.3.1. During this process, the utility billing data that had abnormal energy use was confirmed by the homeowner. Figure 5.31 shows the utility billing data for (a) electricity and (b) natural gas use before the data modification. The dotted lines above and below the 3P model lines were generated to identify the abnormal utility data. The dotted lines were produced using the CV (RMSE) of the 3PC and 3PH model coefficients (i.e., 16.9% for electricity use and 16.4% for natural gas use as shown in Figure 4.18). The outlier in the monthly natural gas data was confirmed with the homeowner. There is no outlier for electricity use in the case-study house #1. The outlier for the natural gas use was for the month of August, 2012, which represented a vacation period when the homeowner was not home. During this period, the homeowner had a thermostat setback which resulted in a small but not abnormal decrease in electricity use. Therefore, the natural gas use for the August 2012 was replaced with a value that was based on 3PH baseload coefficient. Figure 5.32 and Table 5.7 show the modified utility billing data for (a) electricity and (b) natural gas use after the data modification.

The calibration of the as-built case-study house #1 simulation was then carried out using the modified utility billing data. Each parameter was varied from approximately 50% to 150% of its nominal value, in roughly 2% increments, while the



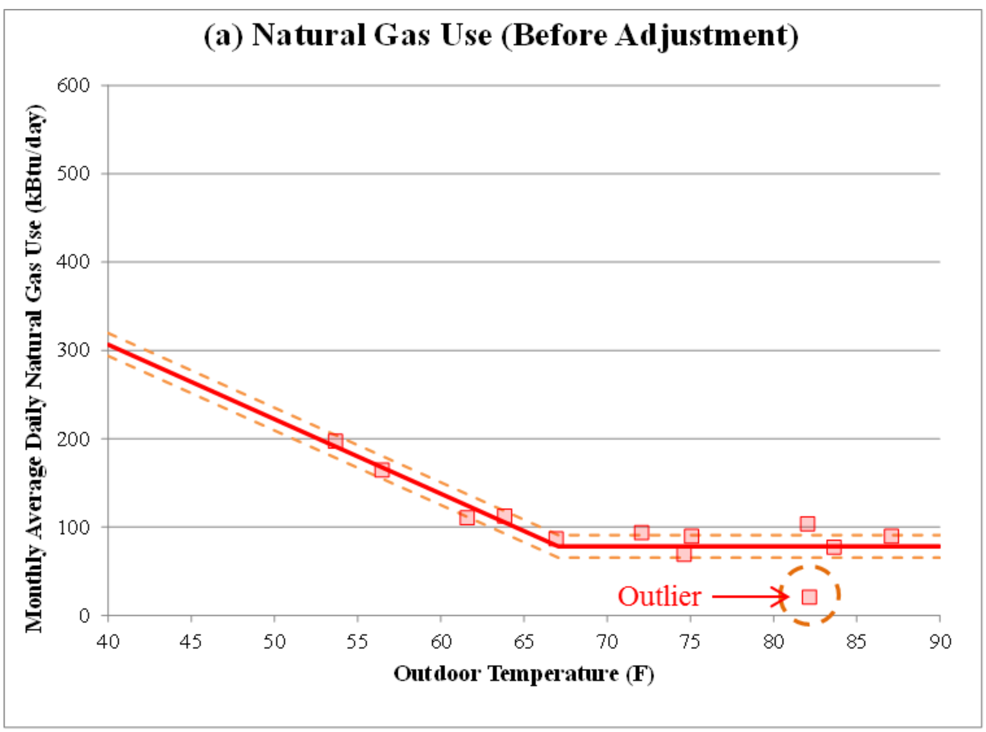
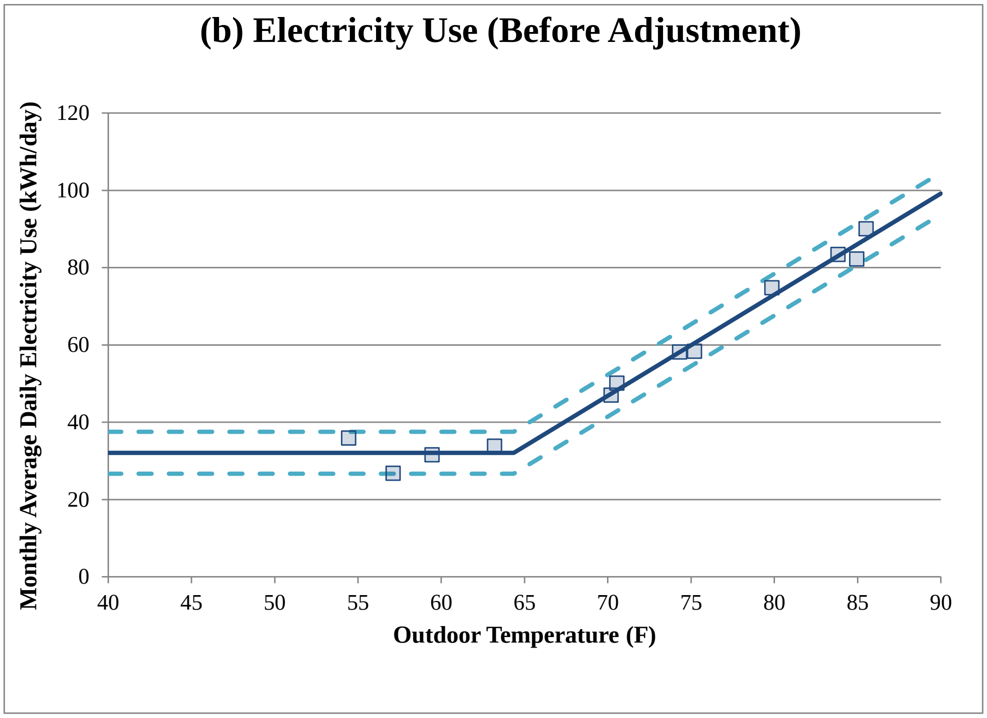


Figure 5.31 Monthly Utility Billing Data for (a) Electricity and (b) Natural Gas Use of House #1 before Data Adjustment



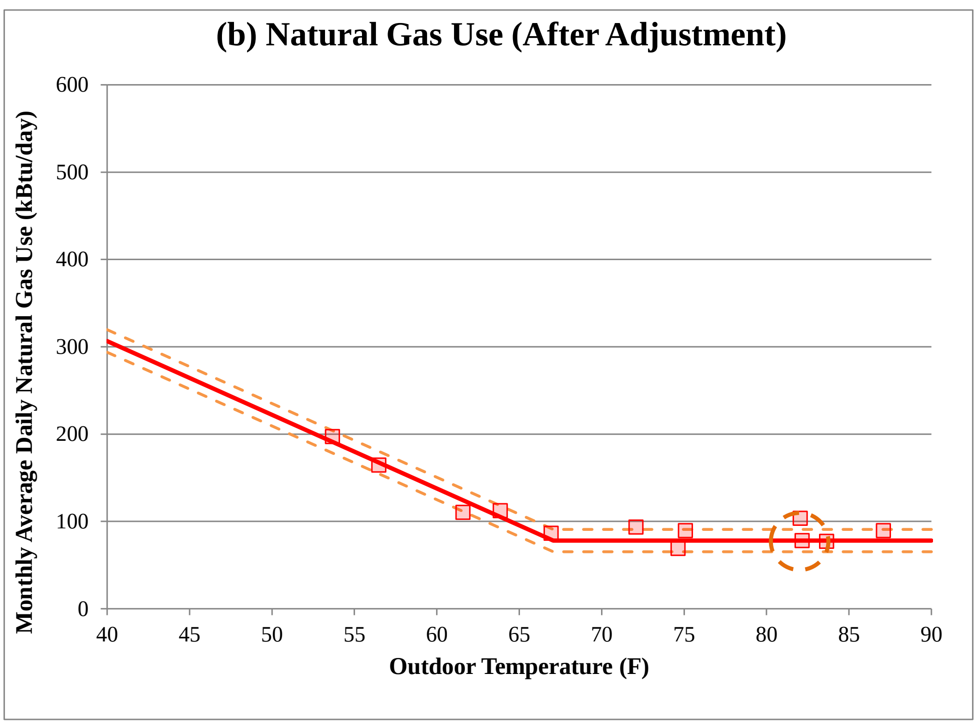


Figure 5.32 Monthly Utility Billing Data for (a) Electricity and (b) Natural Gas Use of House #1 after Data Adjustment

Table 5.7 Modified Monthly Electricity and Natural Gas Utility Billing Data for the Case-study House #1

Billing Period		Days in Billing Periods	Monthly Electricity Use (kWh)	Calculated Monthly Avg. Daily Elec. Use (kWh/Day)
Start Date	**End Date**			
12/9/2011	1/10/2012	33	1184	35.9
1/11/2012	2/8/2012	29	776	26.8
2/9/2012	3/8/2012	29	914	31.5
3/9/2012	4/10/2012	33	1551	47.0
4/11/2012	5/8/2012	28	1628	58.1
5/9/2012	6/11/2012	34	2543	74.8
6/12/2012	7/11/2012	30	2501	83.4
7/12/2012	8/9/2012	29	2610	90.0
8/10/2012	9/11/2012	33	2712	82.2
9/12/2012	10/9/2012	28	1634	58.4
10/10/2012	11/7/2012	29	1453	50.1
11/8/2012	12/7/2012	30	1014	33.8

Billing Period		Days in Billing Periods	Monthly N.G. Use (MCF)	Monthly N.G. Use (MMBtu)	Calculated Monthly Avg. Daily N.G. Use (MMBtu/Day)
Start Date	**End Date**				
12/17/2011	1/18/2012	33	6.5	6.5	0.197
1/19/2012	2/15/2012	28	4.6	4.6	0.164
2/16/2012	3/19/2012	33	3.7	3.7	0.112
3/20/2012	4/18/2012	30	2.8	2.8	0.093
4/19/2012	5/17/2012	29	2	2	0.069
5/18/2012	6/14/2012	28	2.9	2.9	0.104
6/15/2012	7/19/2012	35	2.7	2.7	0.077
7/20/2012	8/16/2012	28	2.5	2.5	0.089
8/17/2012	9/19/2012	34	**2.7**	**2.7**	**0.078**
9/20/2012	10/17/2012	28	2.5	2.5	0.089
10/18/2012	11/15/2012	29	2.5	2.5	0.086
11/16/2012	12/14/2012	29	3.2	3.2	0.110

other parameters were held constant until the parameter value reaching to the minimum global CV (RMSE) had been found. Details about the calibration procedure were described in Section 4.2.5.

In Figure 5.33 through Figure 5.54, two views are presented: Figure (a) presents the global CV (RMSE) using a range of 0% through 100% to show a common scale for all calibrated parameters; Figure (b) shows basically the same plots as Figure (a), but the Y axis has been rescaled to more clearly show the minimum global CV (RMSE).

In this process, the calibrated simulation was begun by adjusting L&E values as shown in Figure 5.33. When the global CV (RMSE) reached its minimum, which is 0.59 of L&E, the adjusted L&E value was then used for next procedure. In the next parameter, the EF values were varied until the minimum global CV (RMSE) was reached as shown in Figure 5.34. This procedure was continued for all 22 parameters. Table 5.8 shows the final parameter values for each calibration procedure. Figure 5.55 shows the minimum global CV (RMSE) changes for all 22 parameters. Figure 5.56 shows how the calibration process impacted the total energy use (i.e., electricity and natural use). As seen from Figure 5.55 and Figure 5.56, it was found that the first two parameters (i.e., the L&E and EF) had the largest impact on calibration with the remaining 20 parameters having considerably less impact. In addition, Figure 5.57 shows the calibrated energy use of the as-built case-study house #1 simulation model against outdoor temperature. The final minimum global CV (RMSE) was 8.78% for the case-study house #1, which is within the accuracy criterion that was previously established.

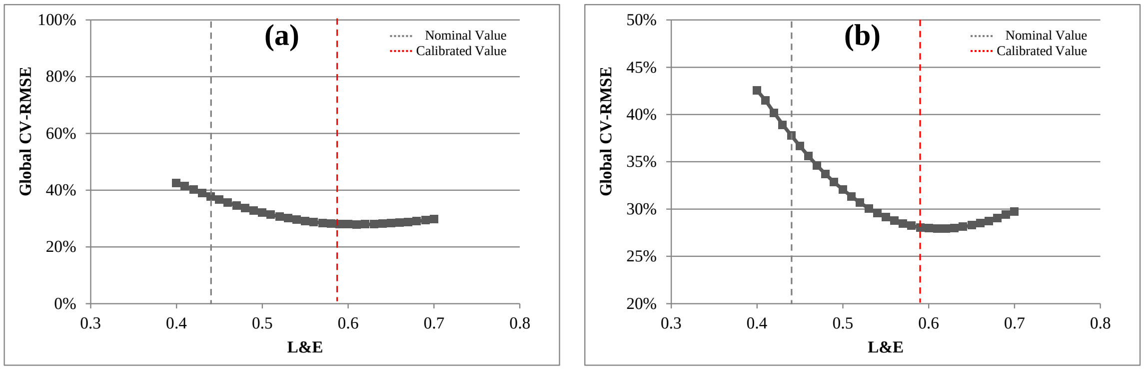


Figure 5.33 Global CV (RMSE) Changes for L&E: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

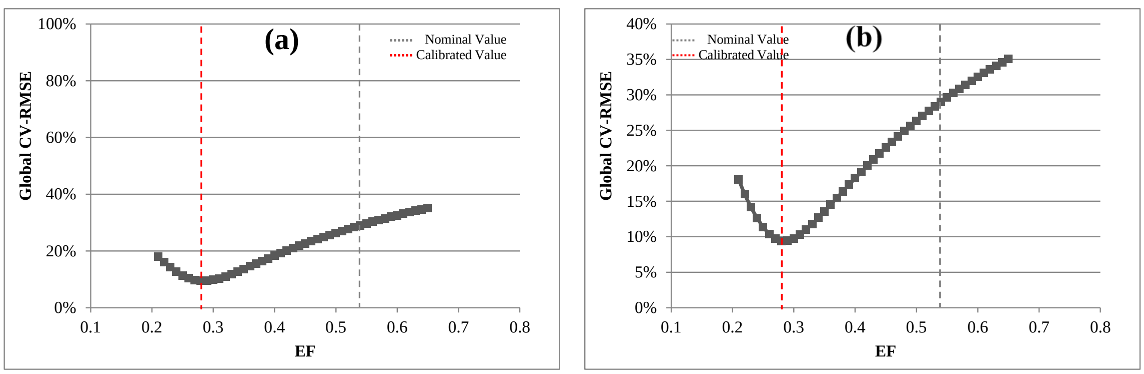


Figure 5.34 Global CV (RMSE) Changes for EF: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

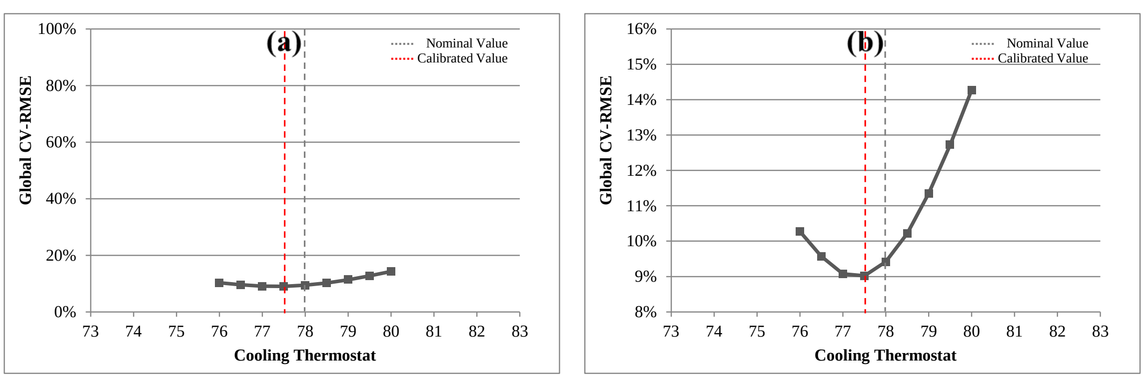


Figure 5.35 Global CV (RMSE) Changes for Cooling Thermostat Set-point Temperature: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

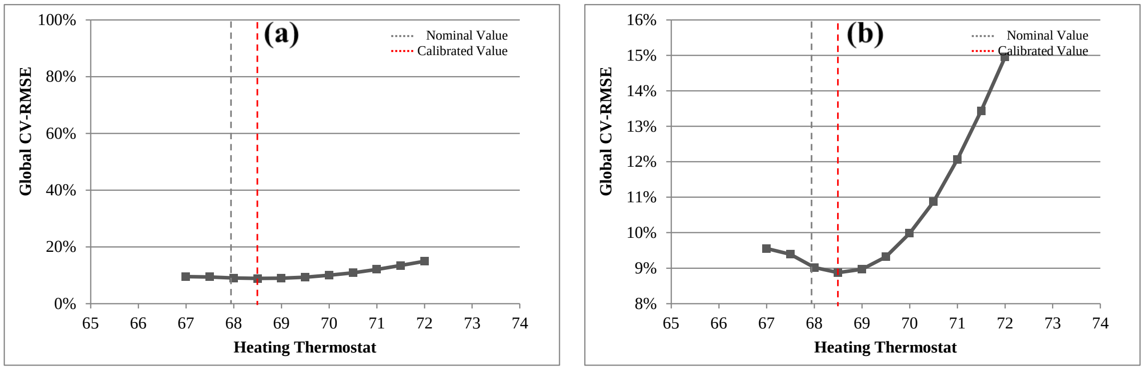


Figure 5.36 Global CV (RMSE) Changes for Heating Thermostat Set-point Temperature: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

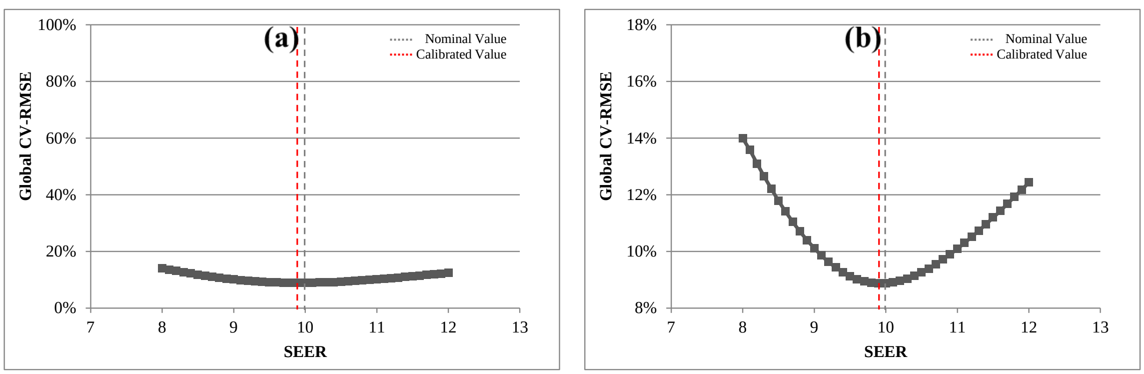


Figure 5.37 Global CV (RMSE) Changes for SEER: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

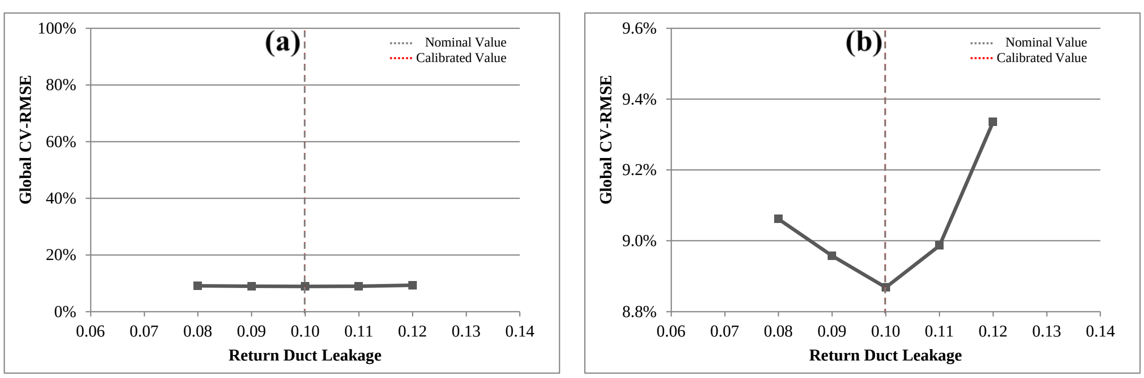


Figure 5.38 Global CV (RMSE) Changes for Return Duct Leakage: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

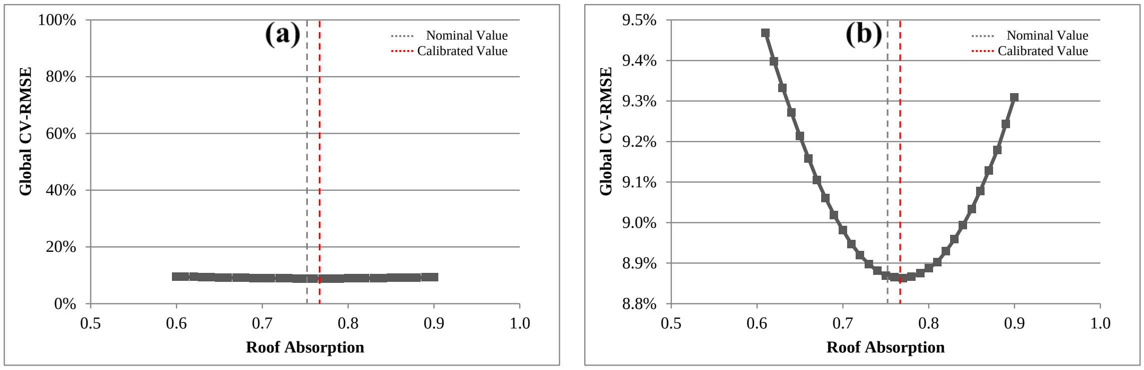


Figure 5.39 Global CV (RMSE) Changes for Roof Absorption: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

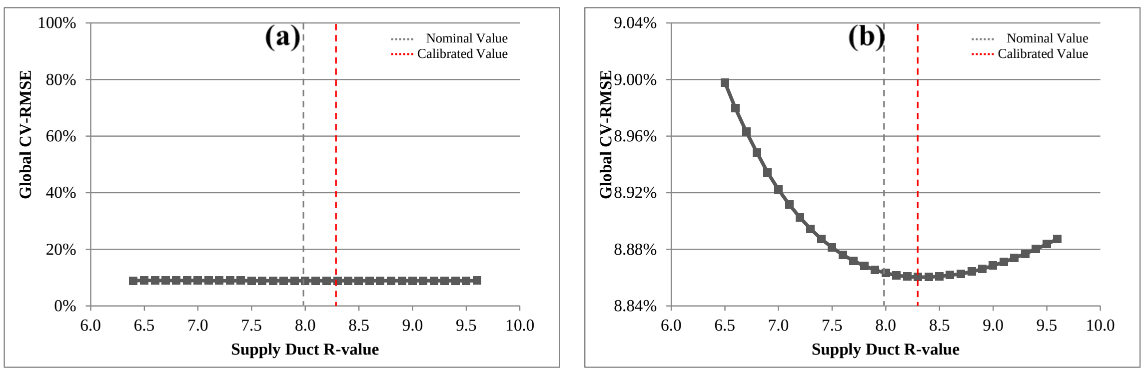


Figure 5.40 Global CV (RMSE) Changes for Supply Duct R-value: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

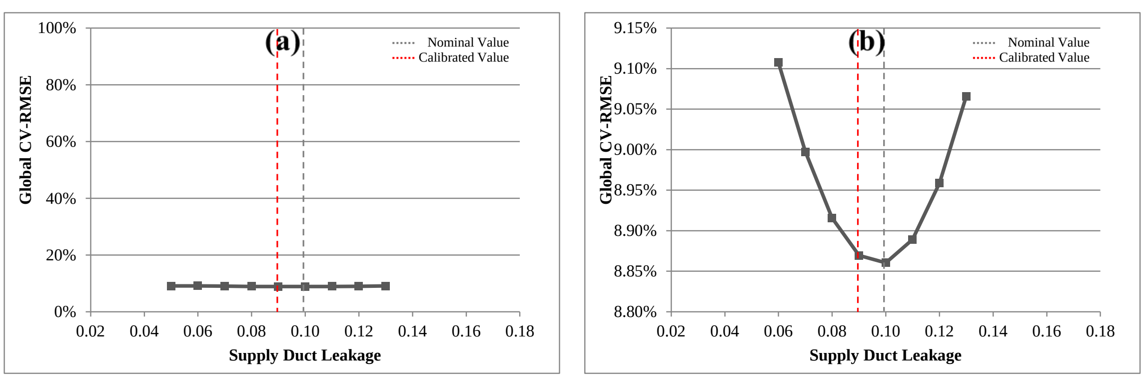


Figure 5.41 Global CV (RMSE) Changes for Supply Duct Leakage: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

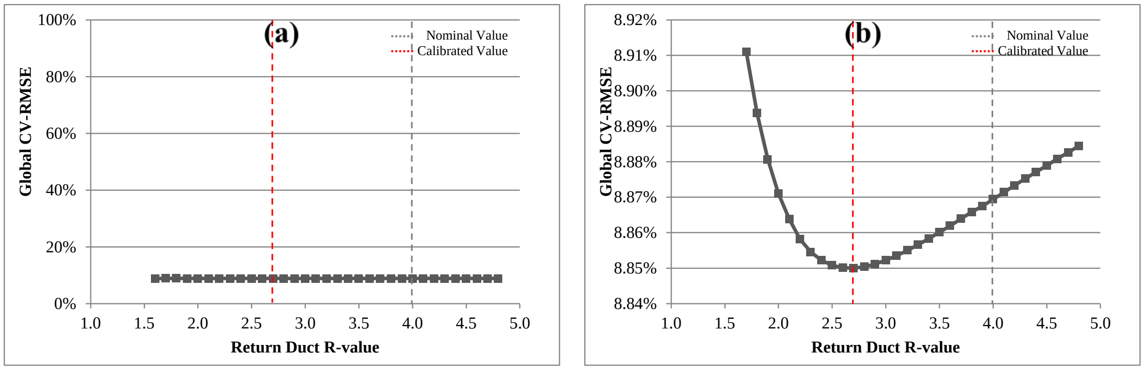


Figure 5.42 Global CV (RMSE) Changes for Return Duct R-value: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

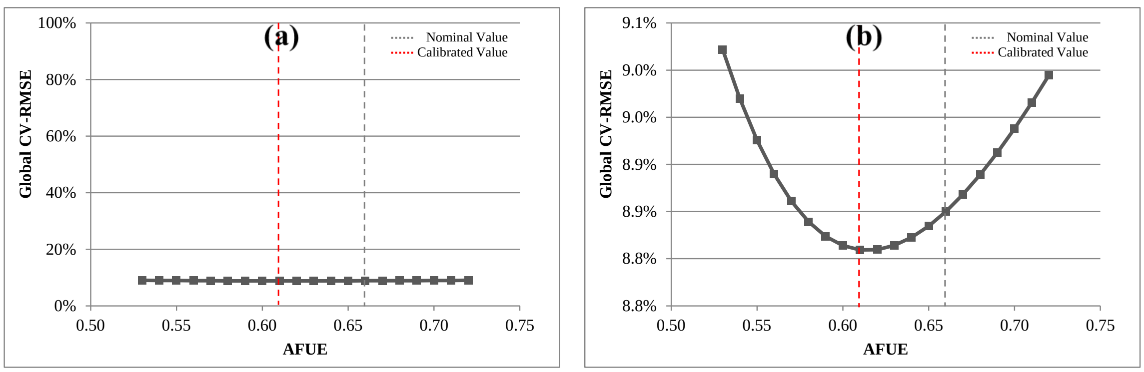


Figure 5.43 Global CV (RMSE) Changes for AFUE: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

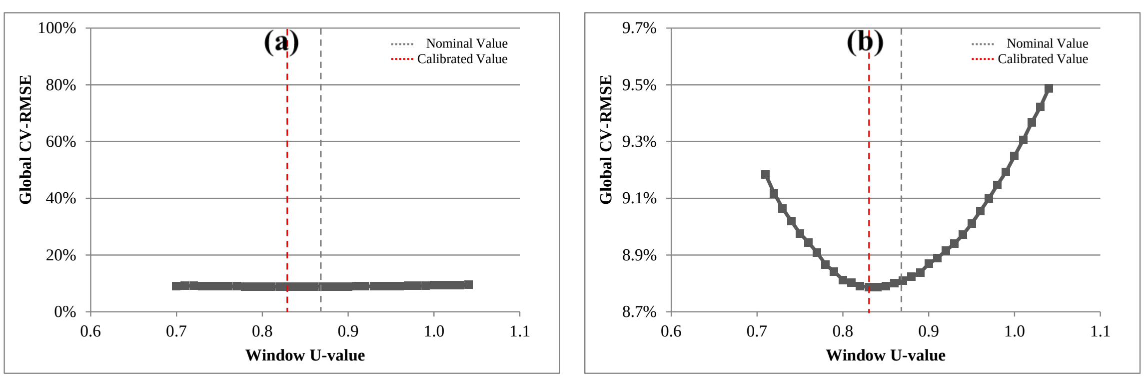


Figure 5.44 Global CV (RMSE) Changes for Window U-value: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

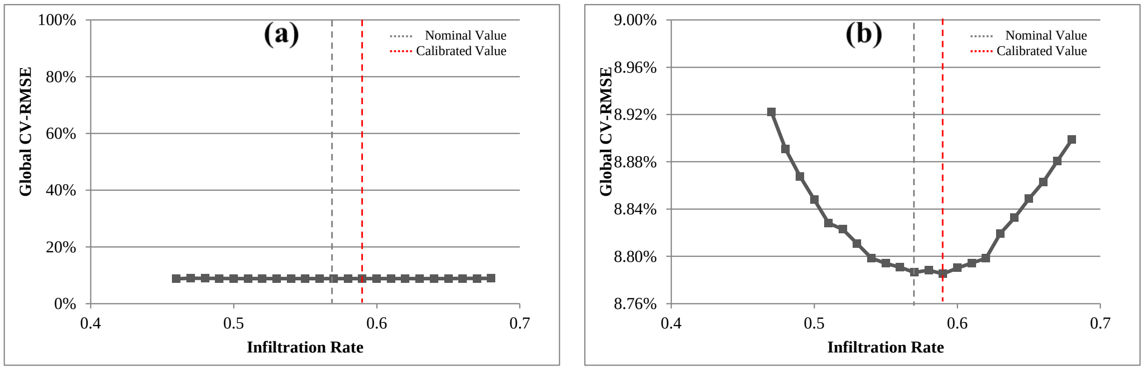


Figure 5.45   *Global CV (RMSE) Changes for Infiltration Rate: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

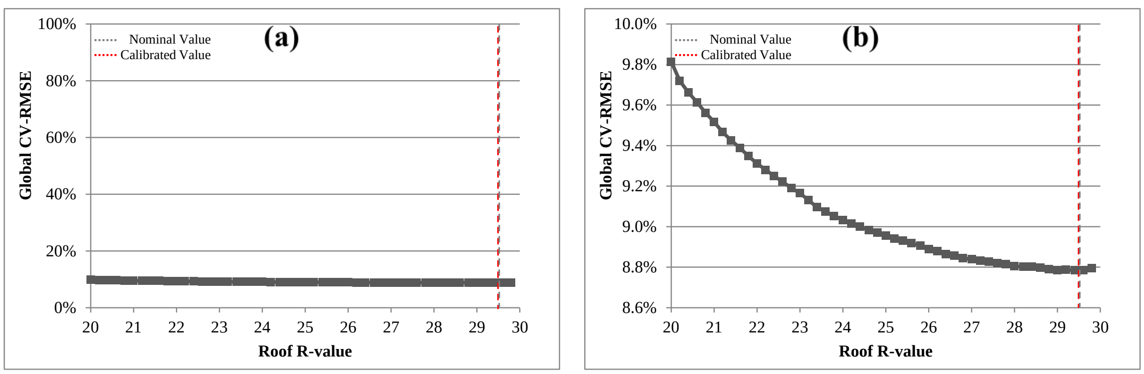


Figure 5.46   *Global CV (RMSE) Changes for Roof R-value: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

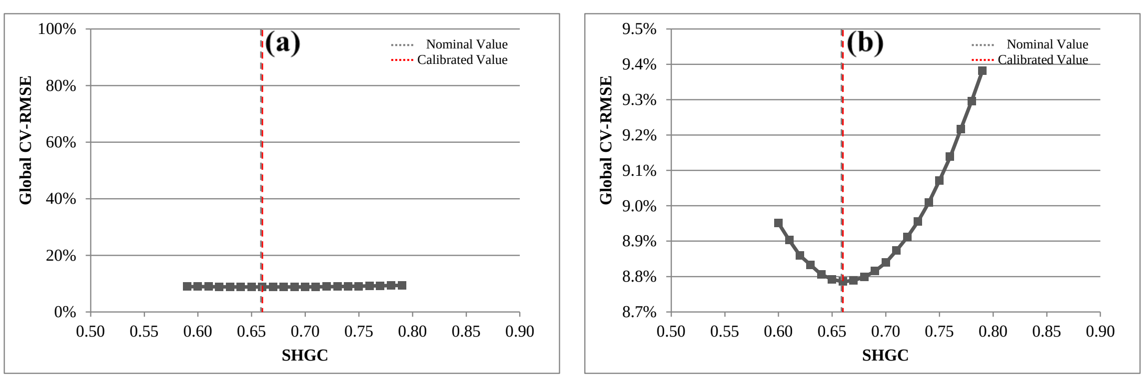


Figure 5.47   *Global CV (RMSE) Changes for SHGC: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

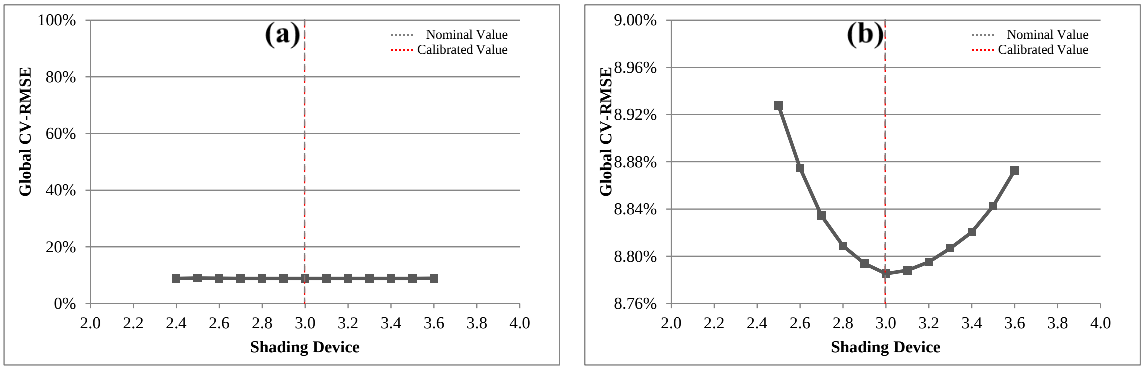


Figure 5.48 Global CV (RMSE) Changes for Shading Devices: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

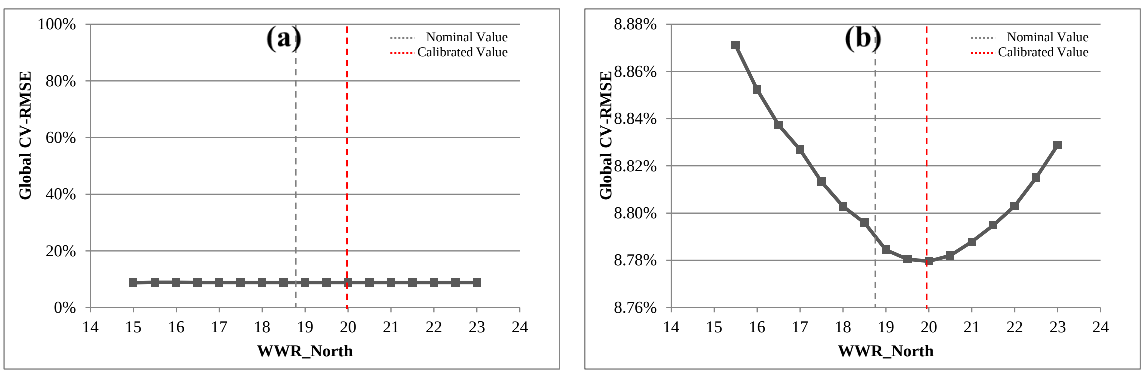


Figure 5.49 Global CV (RMSE) Changes for WWR for North: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

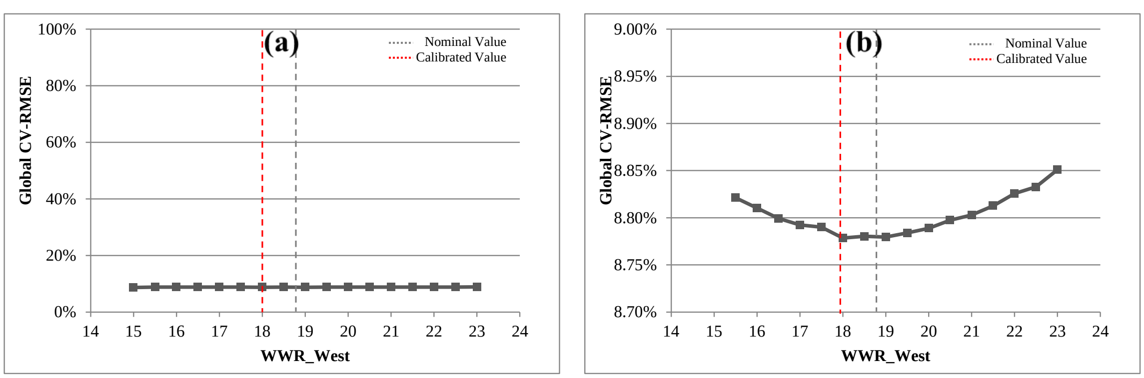


Figure 5.50 Global CV (RMSE) Changes for WWR for West: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

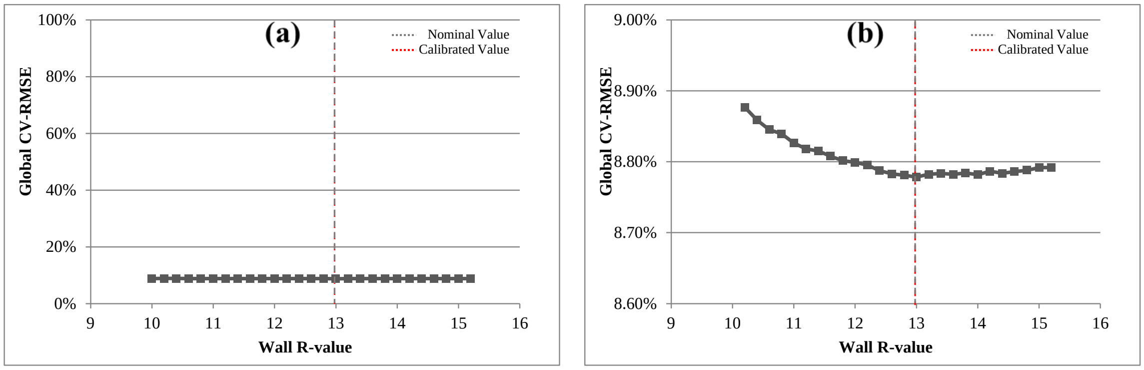


Figure 5.51 *Global CV (RMSE) Changes for Wall R-value: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

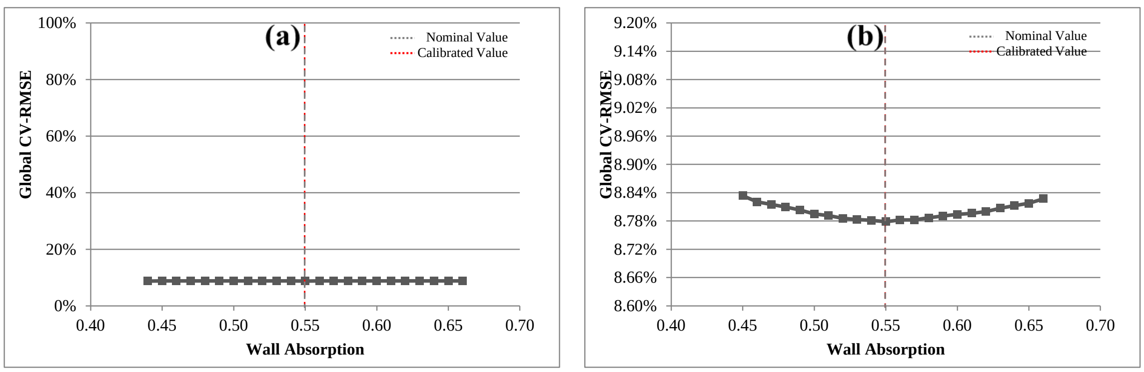


Figure 5.52 *Global CV (RMSE) Changes for Wall Absorption: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

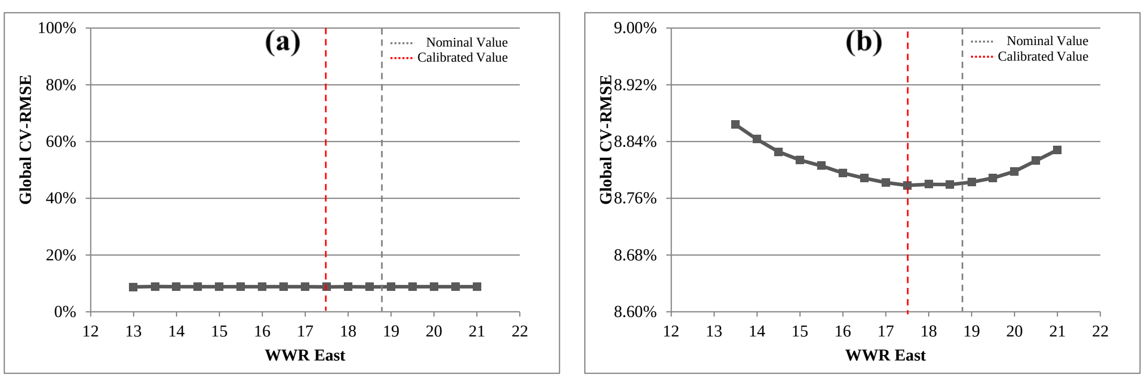


Figure 5.53 *Global CV (RMSE) Changes for WWR for East: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

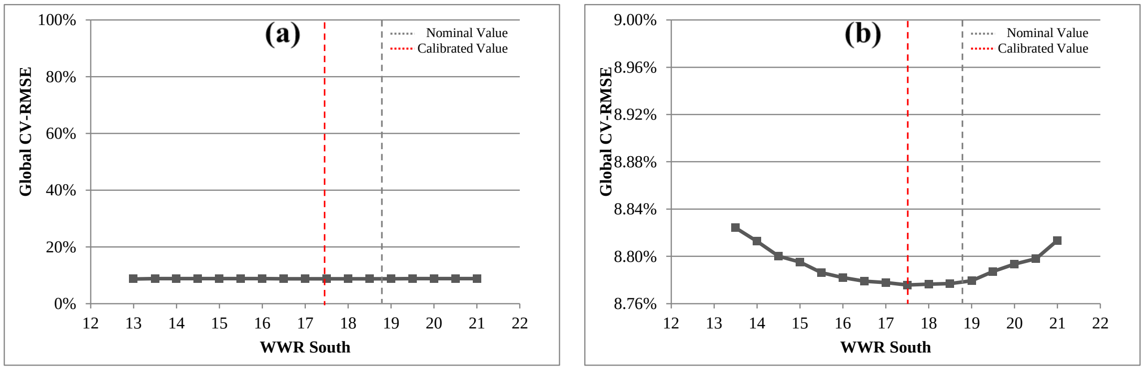


Figure 5.54 Global CV (RMSE) Changes for WWR for South: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

Table 5.8 Each Parameter Value for the As-built House #1 after Calibration Procedure

Calibration Run #	3P Coefficient		Parameter	As-built Simulation	
				Nominal	Calibrated
1	Baseload	Elec.	**L&E**	0.44	0.59
2		N.G.	**EF**	0.525	0.280
3	Change-point	Elec.	**Cooling Thermostat**	78	77.5
4		N.G.	**Heating Thermostat**	68	68.5
5	Slope	Elec.	**SEER**	10.00	9.90
6			**Return Duct Leakage**	0.100	0.100
7			**Roof Absorption**	0.75	0.77
8			**Supply Duct R-value**	8.0	8.3
9			**Supply Duct Leakage**	0.100	0.090
10			**Return Duct R-value**	4.0	2.7
11		N.G.	**AFUE**	0.66	0.61
12			**Window U-value**	0.87	0.83
13			**Infiltration Rate**	0.57	0.59
14			**Roof R-value**	29.6	29.6
15			**SHGC**	0.66	0.66
16			**Shading Devices**	3.0	3.0
17			**WWR North**	18.8	20.0
18			**WWR West**	18.8	18.0
19			**Wall R-value**	13.0	13.0
20			**Wall Absorption**	0.55	0.55
21			**WWR East**	18.8	17.5
22			**WWR South**	18.8	17.5

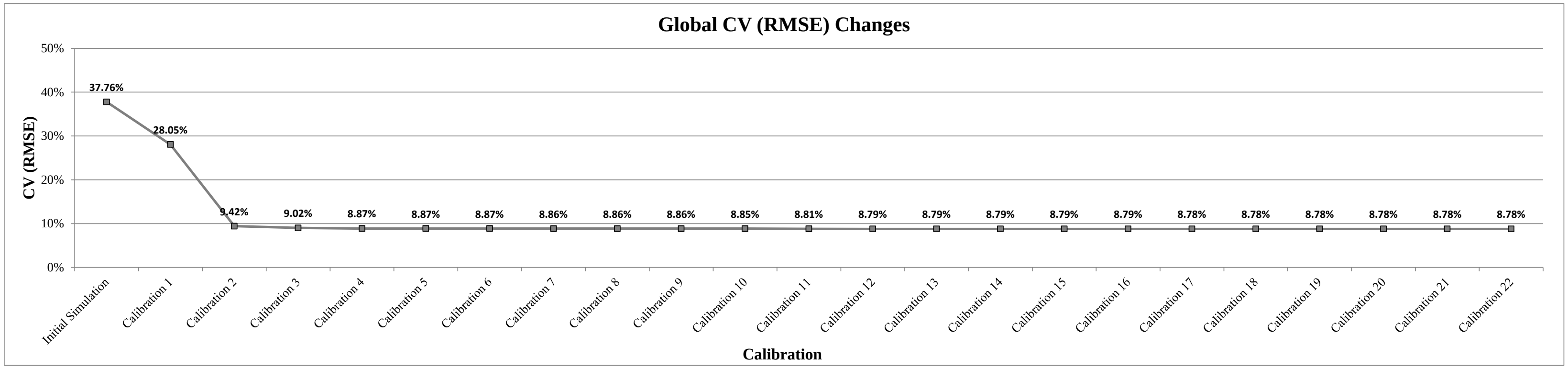


Figure 5.55 CV (RMSE) Changes for the As-built House #1 by Each Calibration Procedure

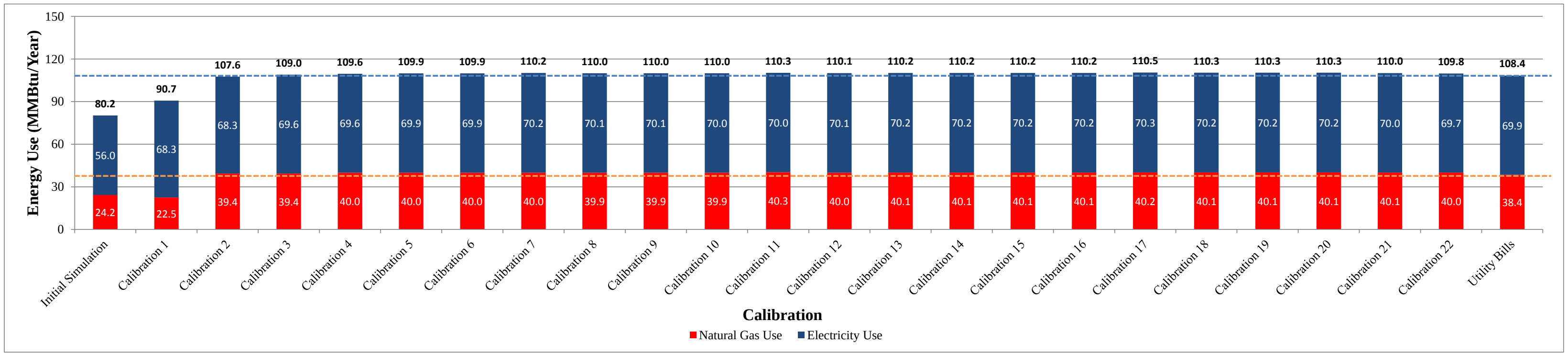
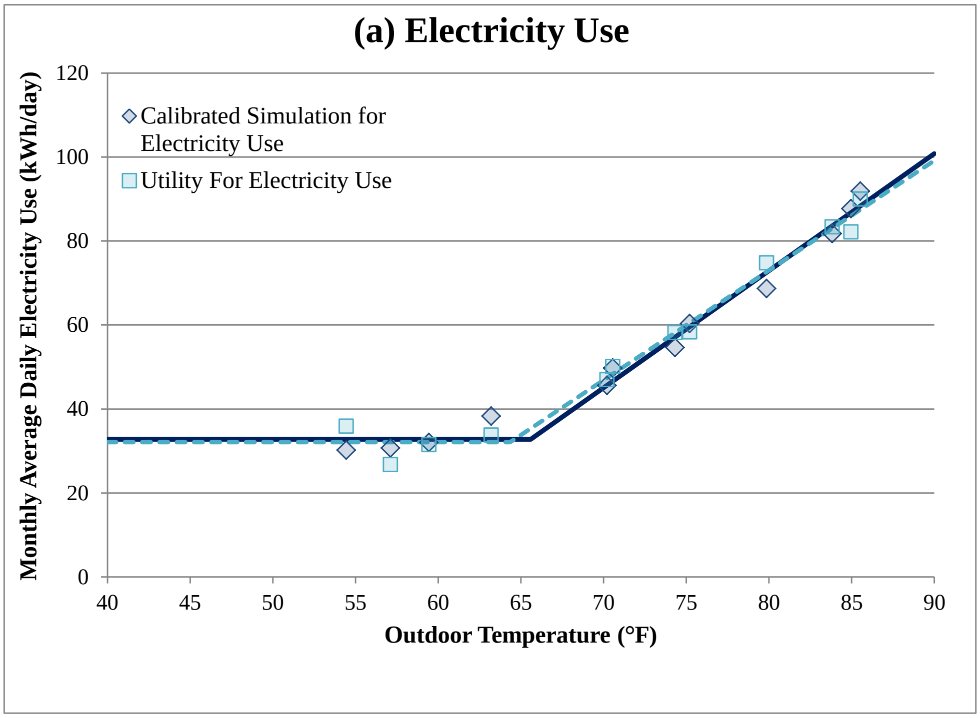


Figure 5.56 Energy Use Changes for the As-built House #1 by Each Calibration Procedure



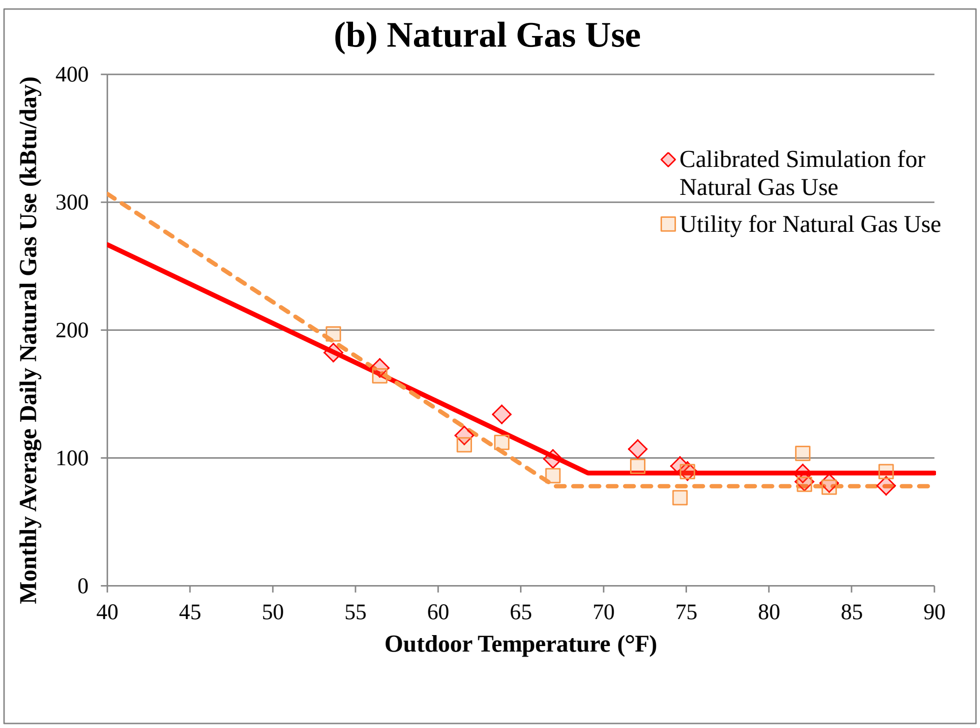


Figure 5.57 Results for the Calibrated As-built House #1 Simulation and Corresponding Three-parameter Change-point Regression Models for: (a) Electricity and (b) Natural Gas Use

5.1.5 Results of Calibration for Easy-to-use Case-study House #1 Simulation

In a similar fashion to the calibration of the as-built case-study house #1 simulation, the calibration of the easy-to-use case-study house #1 simulation was performed using the modified utility billing data.

In Figure 5.58 through Figure 5.79, Figure (a) presents the global CV (RMSE), including the minimum global CV (RMSE), using a 0% through a 100% range to show a common scale for all the calibrated parameters. Figure (b) presents basically the same plots as the Figure (a), but uses a different global CV (RMSE) range in the Y axis to clearly distinguish which parameter values show the minimum global CV (RMSE). The calibrated simulation was begun by first adjusting the L&E values as shown in Figure 5.58, until the global CV (RMSE) reached the minimum, which is 0.55 of L&E, with the adjusted L&E value used for next procedure. In the next parameter, the EF values were varied until the value reached minimum global CV (RMSE) as shown in Figure 5.59. This procedure was continued for all 22 parameters. Table 5.9 shows the final, optimum parameter values from each calibration, and Figure 5.80 shows the cumulative global CV (RMSE) changes. Figure 5.81 shows total energy use changes corresponding to the same parameter changes. As seen from the Figure 5.80 and Figure 5.81, it was found that the first two parameters (i.e., the L&E and the EF adjusted) had a large impact on the calibration, whereas all remaining parameters had only a modest impact. In addition, Figure 5.82 shows the calibrated energy use of the easy-to-use house #1 simulation model against outdoor temperature. The final minimum global CV (RMSE) was 9.11% for the case-study house #1, which is within the accuracy criterion previously established.

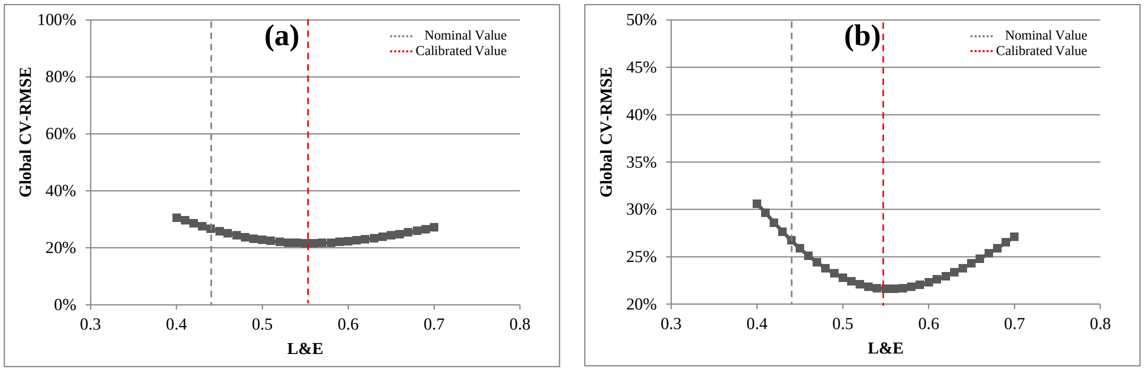


Figure 5.58 Global CV (RMSE) Changes for L&E: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

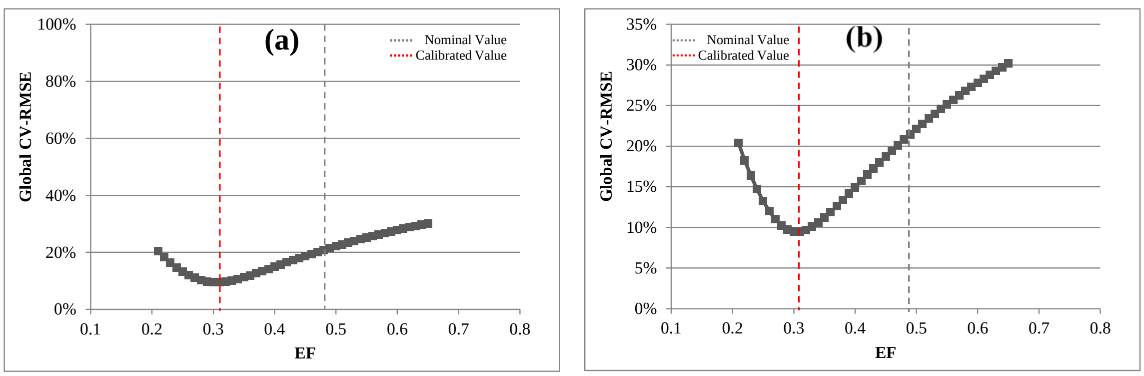


Figure 5.59 Global CV (RMSE) Changes for EF: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

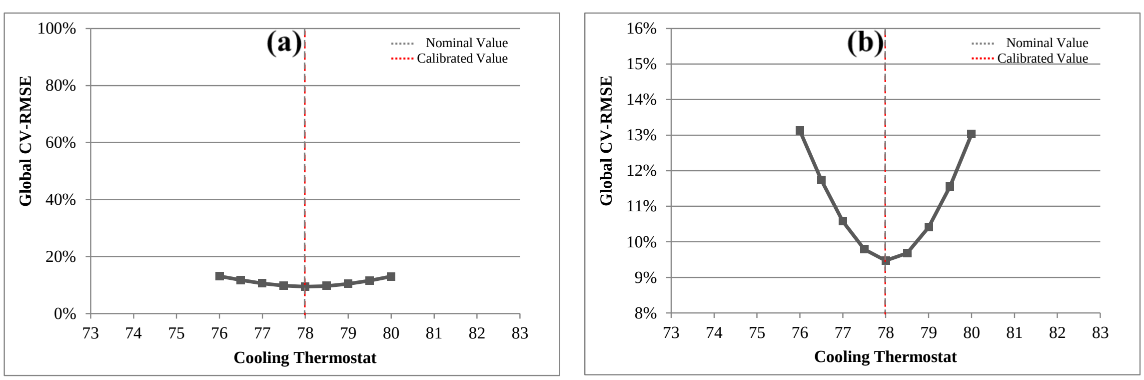


Figure 5.60 Global CV (RMSE) Changes for Cooling Thermostat Set-point Temperature: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

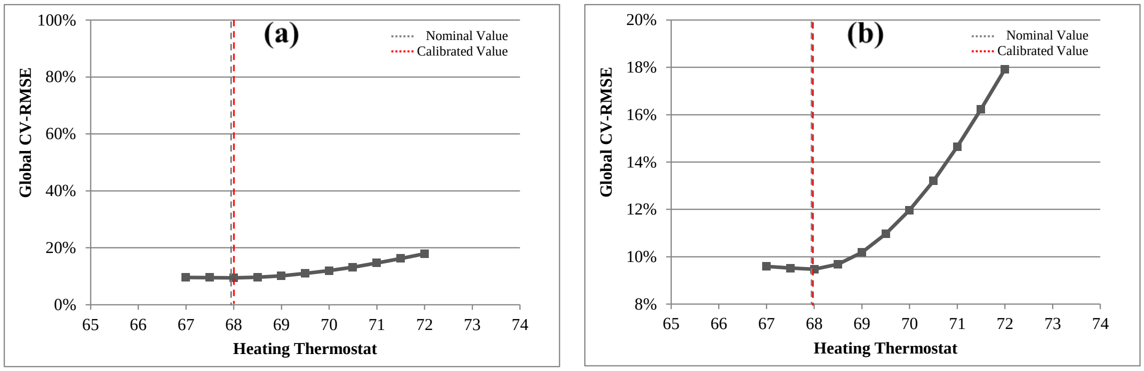


Figure 5.61 Global CV (RMSE) Changes for Heating Thermostat Set-point Temperature: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

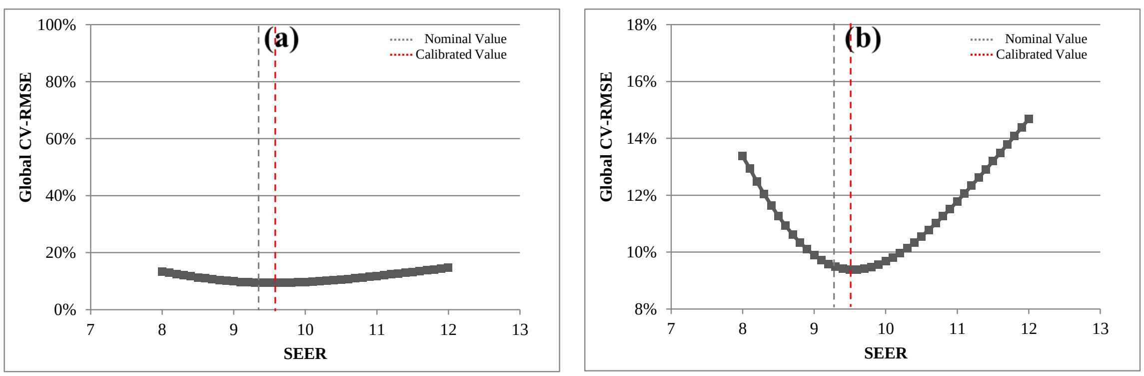


Figure 5.62 Global CV (RMSE) Changes for SEER: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

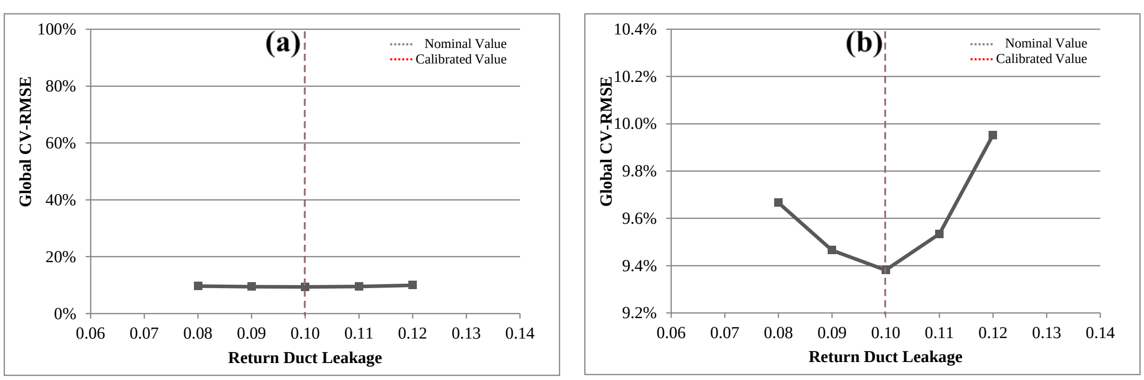


Figure 5.63 Global CV (RMSE) Changes for Return Duct Leakage: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

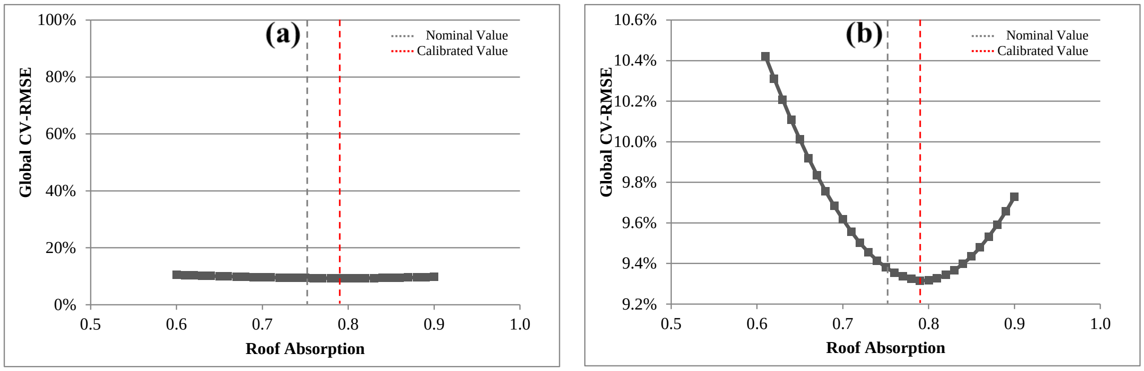


Figure 5.64 Global CV (RMSE) Changes for Roof Absorption: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

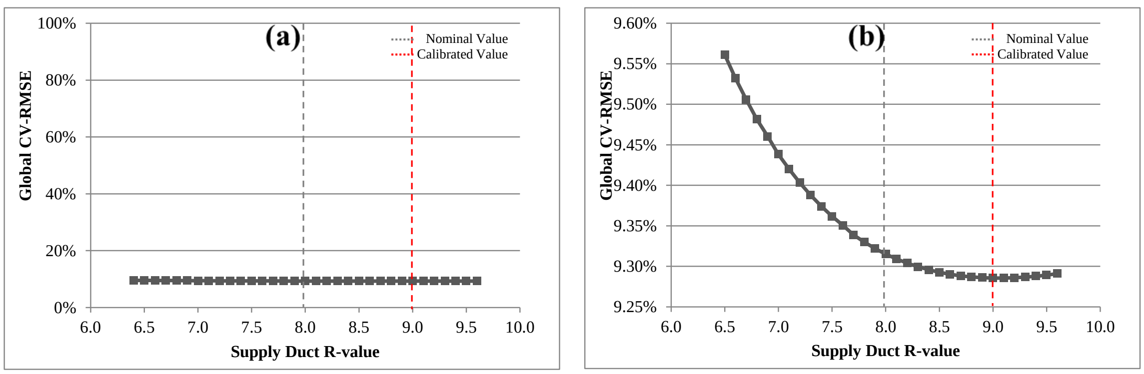


Figure 5.65 Global CV (RMSE) Changes for Supply Duct R-value: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

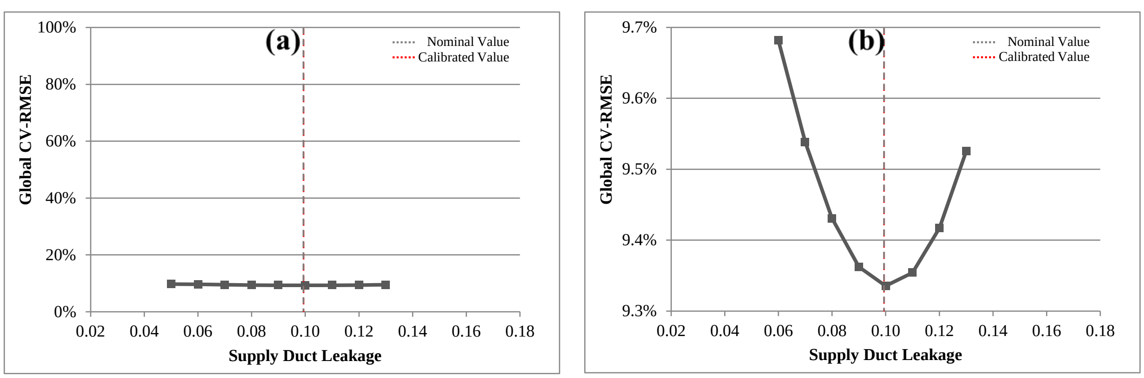


Figure 5.66 Global CV (RMSE) Changes for Supply Duct Leakage: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

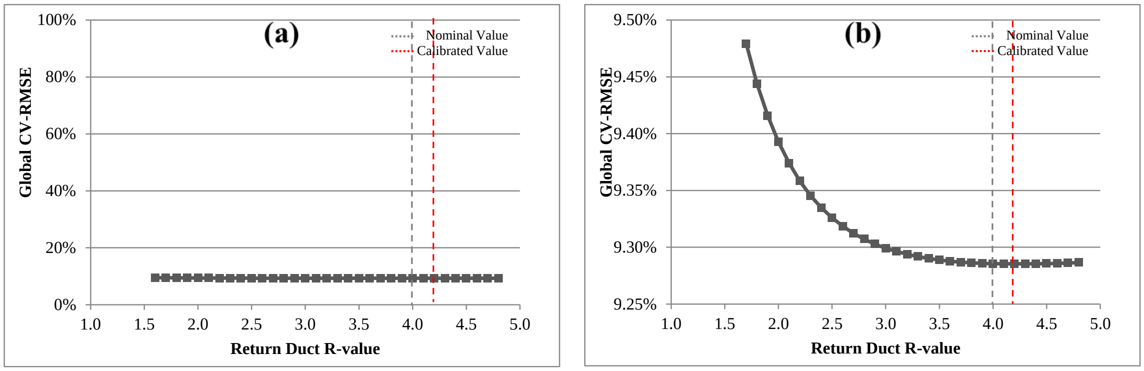


Figure 5.67 *Global CV (RMSE) Changes for Return Duct R-value: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

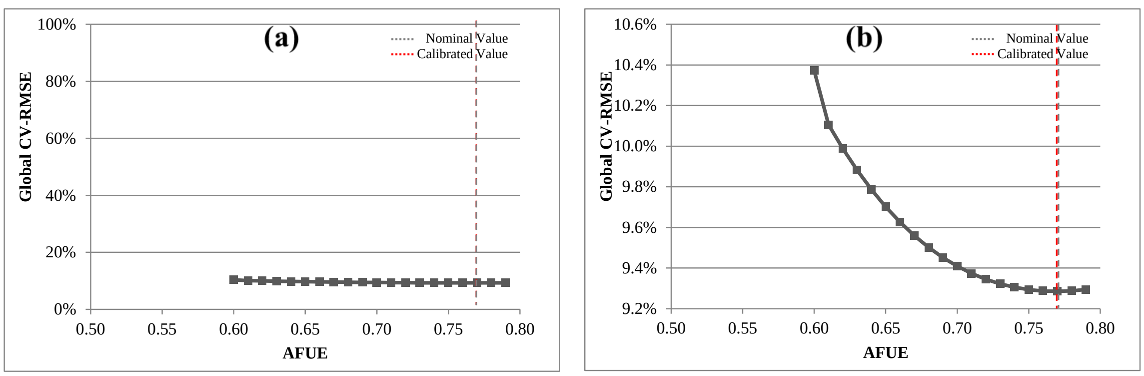


Figure 5.68 *Global CV (RMSE) Changes for AFUE: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

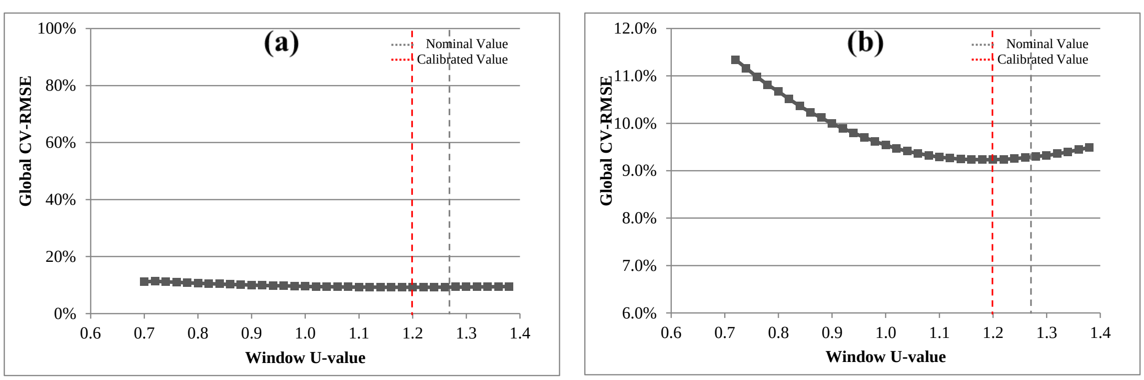


Figure 5.69 *Global CV (RMSE) Changes for Window U-value: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

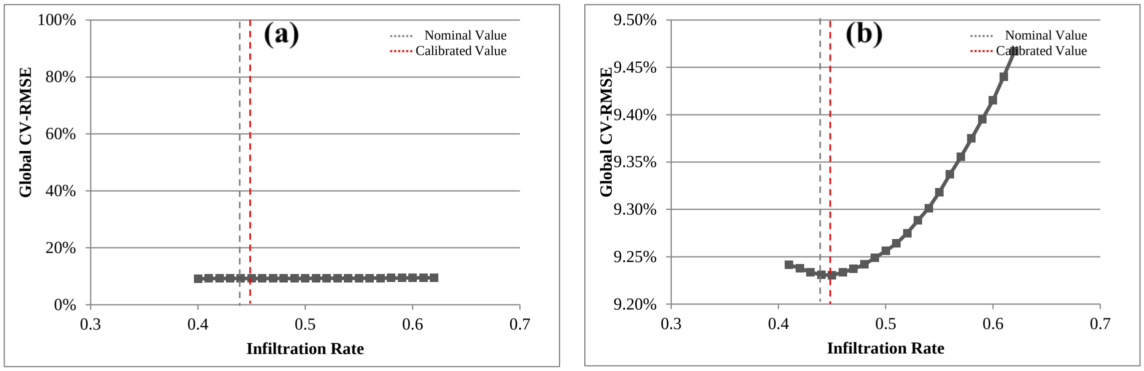


Figure 5.70 Global CV (RMSE) Changes for Infiltration Rate: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

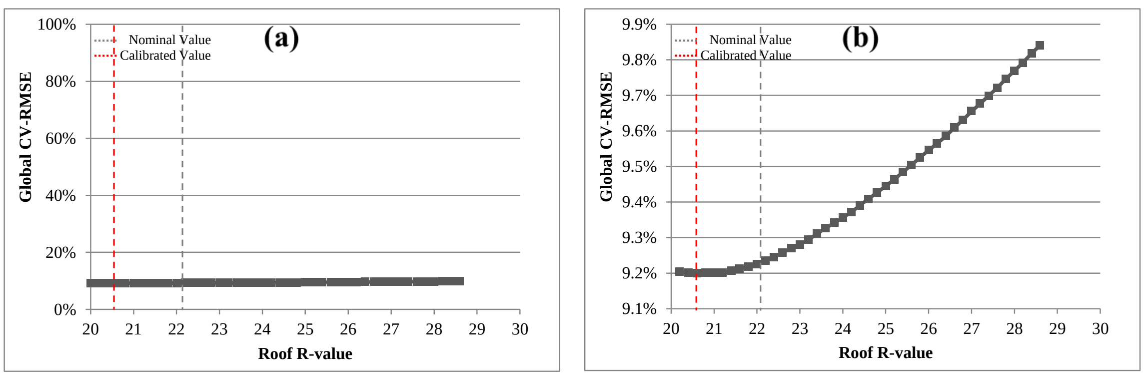


Figure 5.71 Global CV (RMSE) Changes for Roof R-value: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

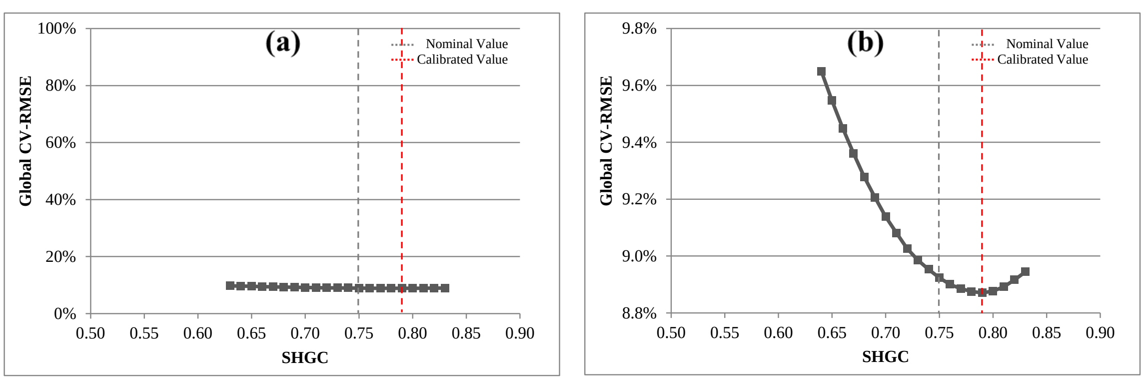


Figure 5.72 Global CV (RMSE) Changes for SHGC: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

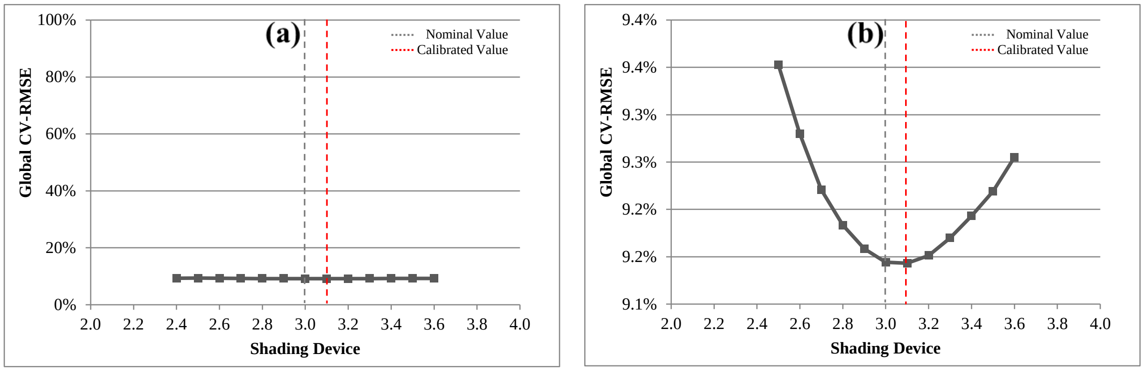


Figure 5.73 Global CV (RMSE) Changes for Shading Devices: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

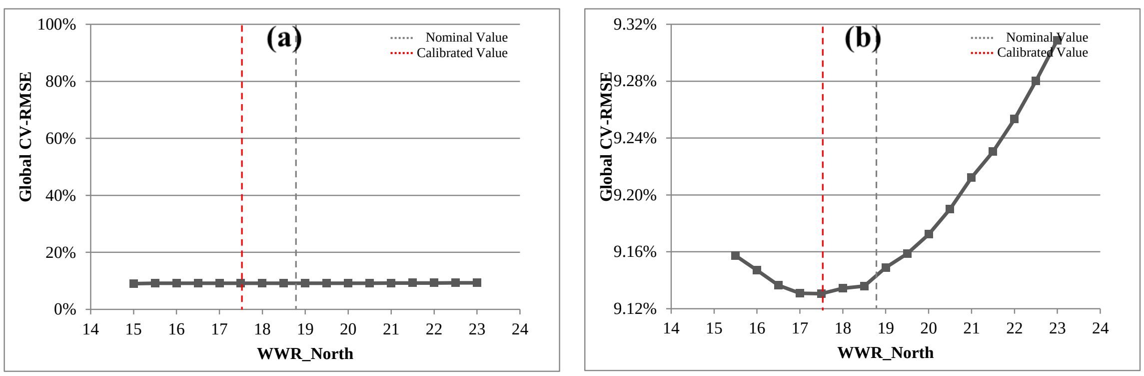


Figure 5.74 Global CV (RMSE) Changes for WWR for North: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

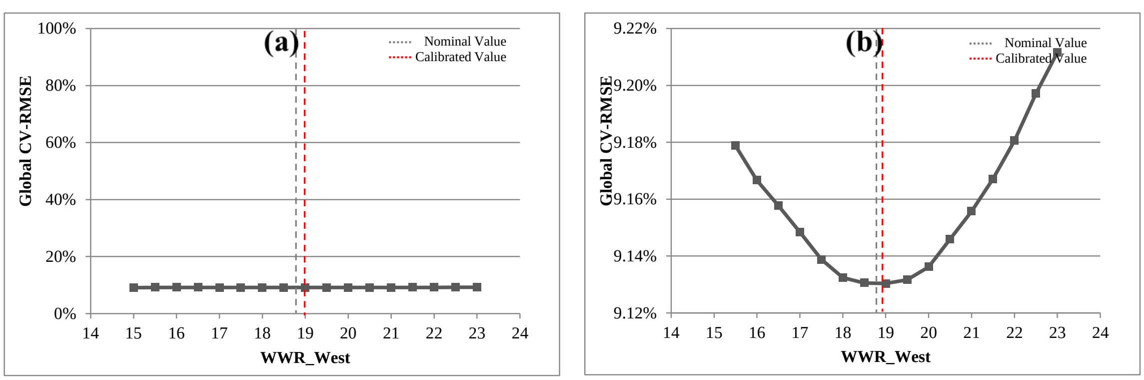


Figure 5.75 Global CV (RMSE) Changes for WWR for West: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

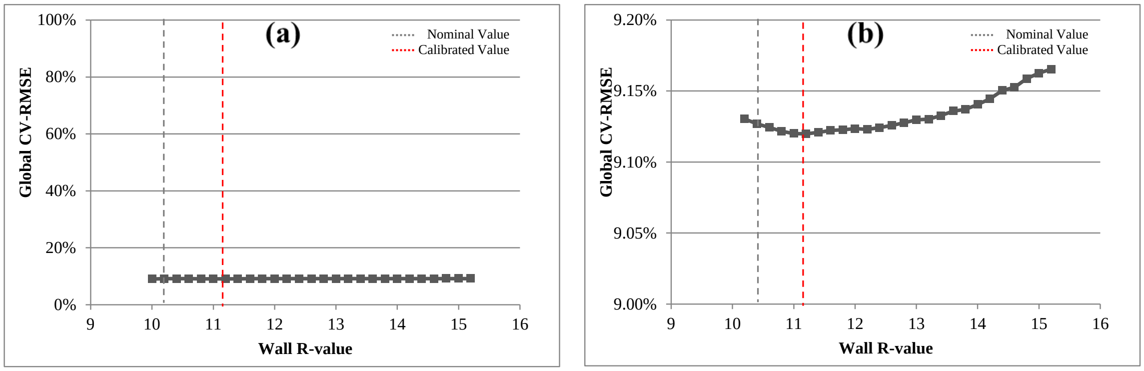


Figure 5.76 Global CV (RMSE) Changes for Wall R-value: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

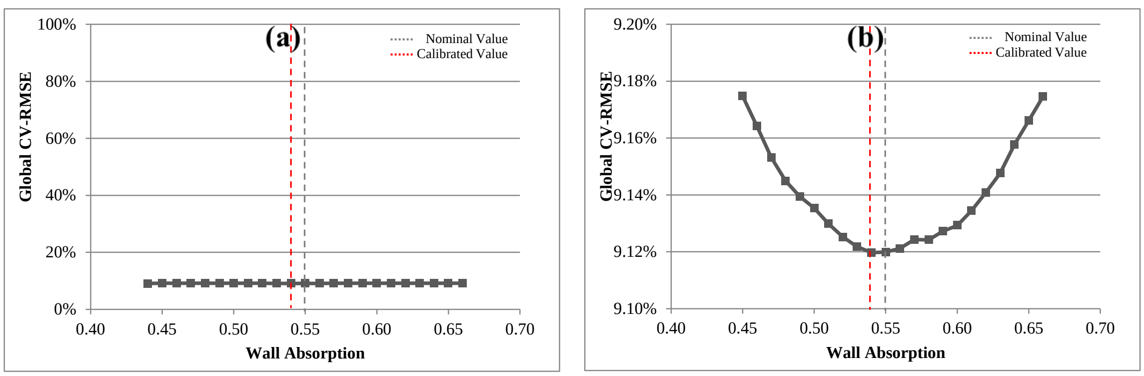


Figure 5.77 Global CV (RMSE) Changes for Wall Absorption: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

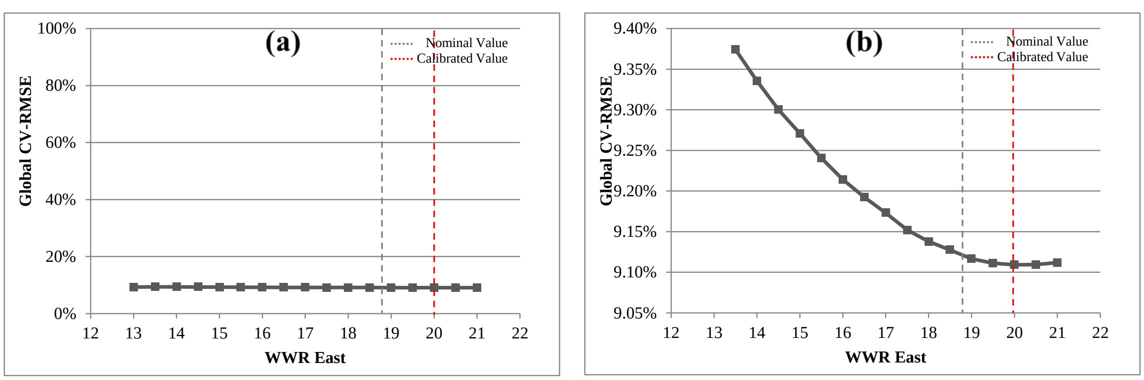


Figure 5.78 Global CV (RMSE) Changes for WWR for East: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

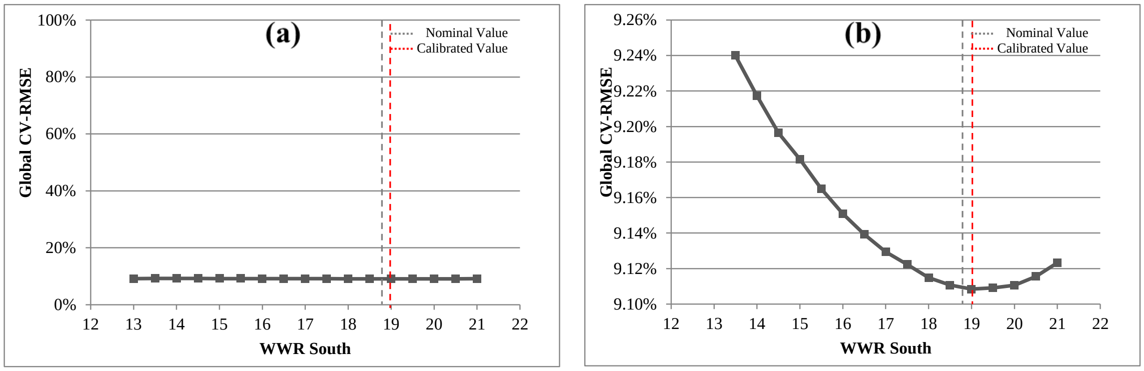


Figure 5.79 Global CV (RMSE) Changes for WWR for South: (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

Table 5.9 Each Parameter Value for the Easy-to-use House #1 after Calibration Procedure

Calibration Run #	3P Coefficient		Parameter	Easy-to-use Simulation	
				Nominal	Calibrated
1	Baseload	Elec.	**L&E**	0.44	0.55
2		N.G.	**EF**	0.492	0.310
3	Change-point	Elec.	**Cooling Thermostat**	78	78
4		N.G.	**Heating Thermostat**	68	68
5	Slope	Elec.	**SEER**	9.31	9.6
6			**Return Duct Leakage**	0.100	0.100
7			**Roof Absorption**	0.75	0.79
8			**Supply Duct R-value**	8.0	9
9			**Supply Duct Leakage**	0.100	0.100
10			**Return Duct R-value**	4.0	4.2
11		N.G.	**AFUE**	0.77	0.77
12			**Window U-value**	1.27	1.20
13			**Infiltration Rate**	0.44	0.45
14			**Roof R-value**	22.13	20.40
15			**SHGC**	0.75	0.79
16			**Shading Devices**	3.0	3.1
17			**WWR North**	18.8	17.5
18			**WWR West**	18.8	19
19			**Wall R-value**	10.2	11.2
20			**Wall Absorption**	0.55	0.54
21			**WWR East**	18.8	20
22			**WWR South**	18.8	19.0

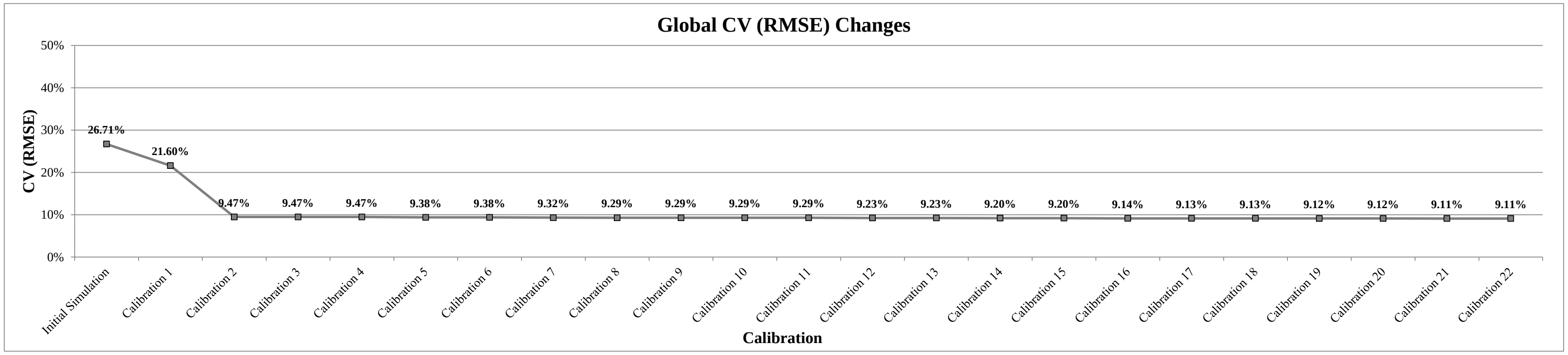


Figure 5.80 CV (RMSE) Changes for the Easy-to-use House #1 by Each Calibration Procedure

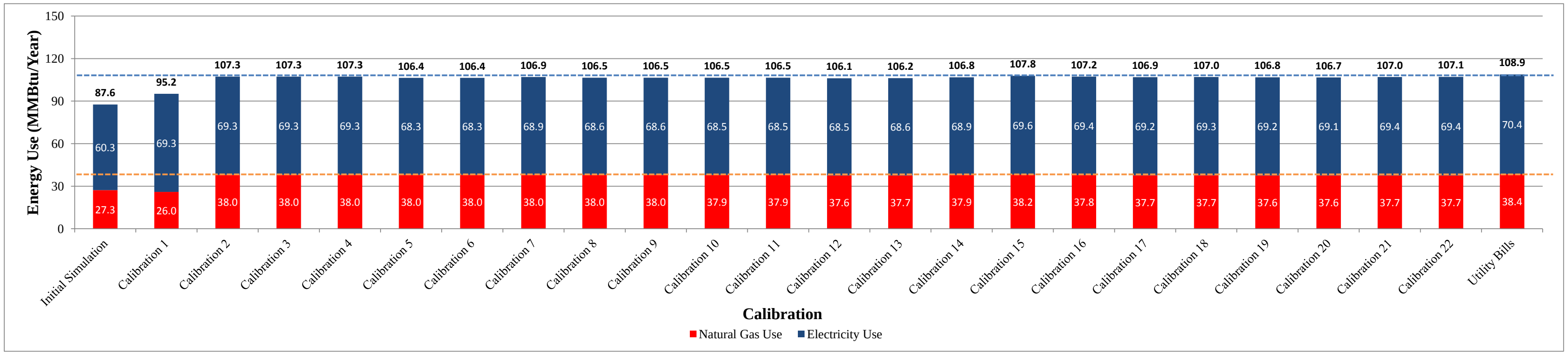
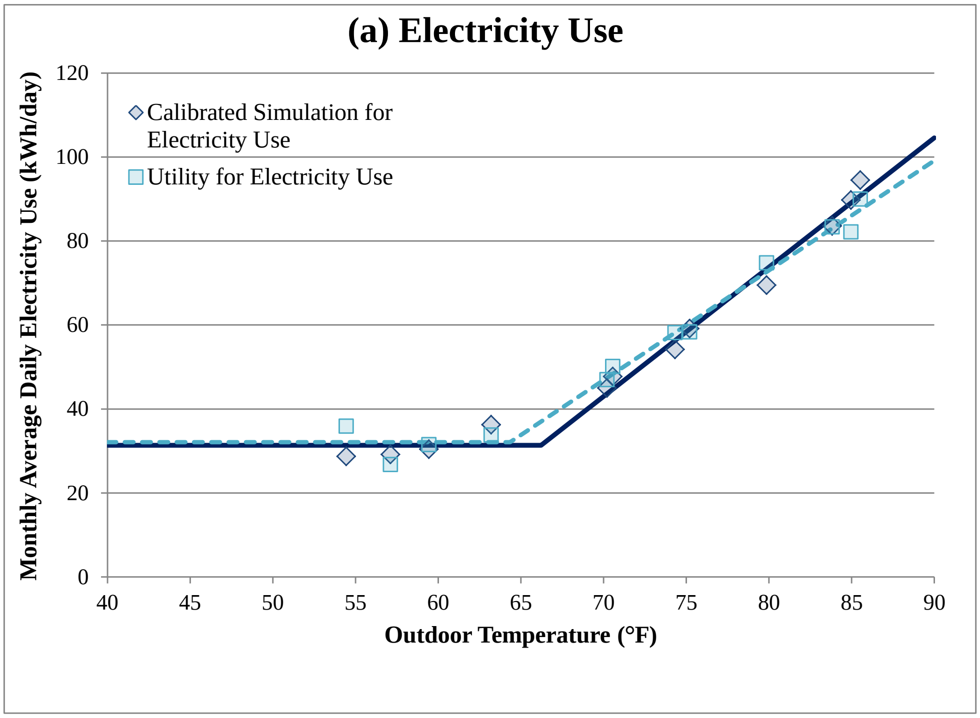


Figure 5.81 Energy Use Changes for the Easy-to-use House #1 by Each Calibration Procedure



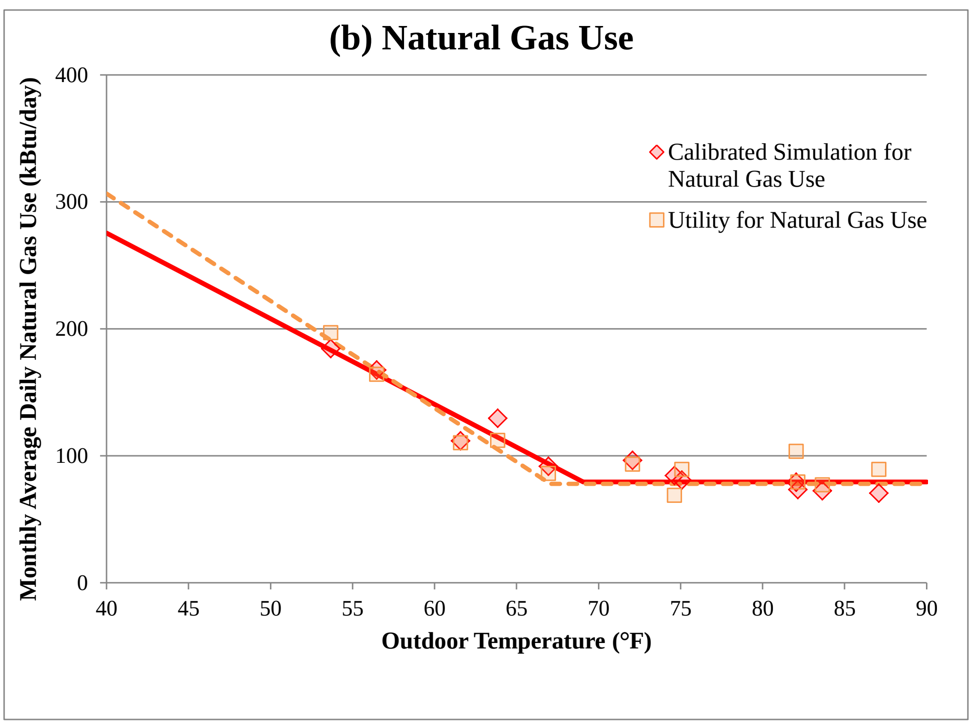


Figure 5.82 Results for the Calibrated Easy-to-use House #1 Simulation and Corresponding Three-parameter Change-point Regression Models for: (a) Electricity and (b) Natural Gas Use

5.1.6 Comparison of the Results of Calibration for the As-built and the Easy-to-use Case-study House #1 Simulations

The case-study house #1 that was modeled using the as-built and the easy-to-use simulations are compared in this section to verify the accuracy of calibration that was performed using the easy-to-use simulation. First, the global CV (RMSE) for the as-built and the easy-to-use calibrated simulations were calculated as 8.78% and 9.11%, respectively, which represent a 0.33% difference between two models. The CV (RMSE) for the electricity and natural gas were also calculated for the as-built and easy-to-use simulations as 6.83% and 7.60% for electricity and 12.67% and 12.42% for natural gas use, respectively, which vary by only 1% between the two models. In addition, the monthly global CV (RMSE) for both models was within 15%, which is within the tolerance range recommended in ASHRAE Guideline 14-2002 (ASHRAE 2002).

Table 5.10 presents a comparison of the calibrated simulation parameters for the as-built and the easy-to-use simulations, and Figure 5.83 presents plots of each calibrated parameters for both models (i.e., as-built vs. easy-to-use) along with the percent difference between them, which include: (a) L&E, (b) EF, (c) cooling thermostat, (d) heating thermostat, (e) SEER, (f) return duct leakage, (g) roof absorption, (h) supply duct R-value, (i) supply duct leakage, (j) return duct R-value, (k) AFUE, (l) window U-value, (m) infiltration rate, (n) roof R-value, (o) SHGC, (p) shading device, (q) WWR for north, (r) WWR for west, (s) wall R-value, (t) wall absorption, (u) WWR for east and (v) WWR for south.

As shown in Figure 5.83, the most influential parameters for the calibrated simulation were (a) L&E and (b) EF. The calibrated simulation parameter values for these parameters were within 7.3% for the L&E and 9.7% for the EF. For the other parameters, such as the supply duct leakage, the difference in the parameter values between the two models was 10.0%; for the return duct R-value (35.7%); the AFUE (20.8%); the window U-value (30.8%); the infiltration rate (31.1%); the roof R-value (45.16%); the SHGC (16.5%); the WWR for north wall (14.3%); the wall R-value (16.1%), and the WWR for east wall (12.5%). The remaining parameters had differences of 10% of the values for both models.

The comparison of the calibrated simulation parameters between the as-built and the easy-to-use simulations implies that the calibrated simulation parameter values can be influenced by other parameters' initial values during previous of simulations. However, the most influential parameters for both calibrations had only a small difference between two calibrated values. Therefore, the easy-to-use simulation can be used as the as-built simulation when using this calibration methodology.

Table 5.10 Comparison of Calibrated Simulation Parameter Values for the As-built and the Easy-to-use Simulations

Calibration Run #	3P Coefficient		Parameter	As-built Simulation		Easy-to-use Simulation		% Diff. of Cali. Sim.
				Nominal	Calibrated	Nominal	Calibrated	
1	Baseload	Elec.	**L&E**	0.44	0.59	0.44	0.55	7.3%
2		N.G.	**EF**	0.525	0.280	0.492	0.310	9.7%
3	Change-point	Elec.	**Cooling Thermostat**	78	77.5	78	78	0.6%
4		N.G.	**Heating Thermostat**	68	68.5	68	68	0.7%
5	Slope	Elec.	**SEER**	10.00	9.90	9.31	9.6	3.1%
6			**Return Duct Leakage**	0.100	0.100	0.100	0.100	0.0%
7			**Roof Absorption**	0.75	0.77	0.75	0.79	2.5%
8			**Supply Duct R-value**	8.0	8.3	8.0	9	7.8%
9			**Supply Duct Leakage**	0.100	0.090	0.100	0.100	10.0%
10			**Return Duct R-value**	4.0	2.7	4.0	4.2	35.7%
11		N.G.	**AFUE**	0.66	0.61	0.77	0.77	20.8%
12			**Window U-value**	0.87	0.83	1.27	1.20	30.8%
13			**Infiltration Rate**	0.57	0.59	0.44	0.45	31.1%
14			**Roof R-value**	29.6	29.6	22.13	20.40	45.1%
15			**SHGC**	0.66	0.66	0.75	0.79	16.5%
16			**Shading Devices**	3.0	3.0	3.0	3.1	3.2%
17			**WWR North**	18.8	20.0	18.8	17.5	14.3%
18			**WWR West**	18.8	18.0	18.8	19	5.3%
19			**Wall R-value**	13.0	13.0	10.2	11.2	16.1%
20			**Wall Absorption**	0.55	0.55	0.55	0.54	1.9%
21			**WWR East**	18.8	17.5	18.8	20	12.5%
22			**WWR South**	18.8	17.5	18.8	19.0	7.9%
Elec. CV-RMSE				6.83%		7.60%		
N.G. CV-RMSE				12.67%		12.42%		
Global CV-RMSE				8.78%		9.11%		

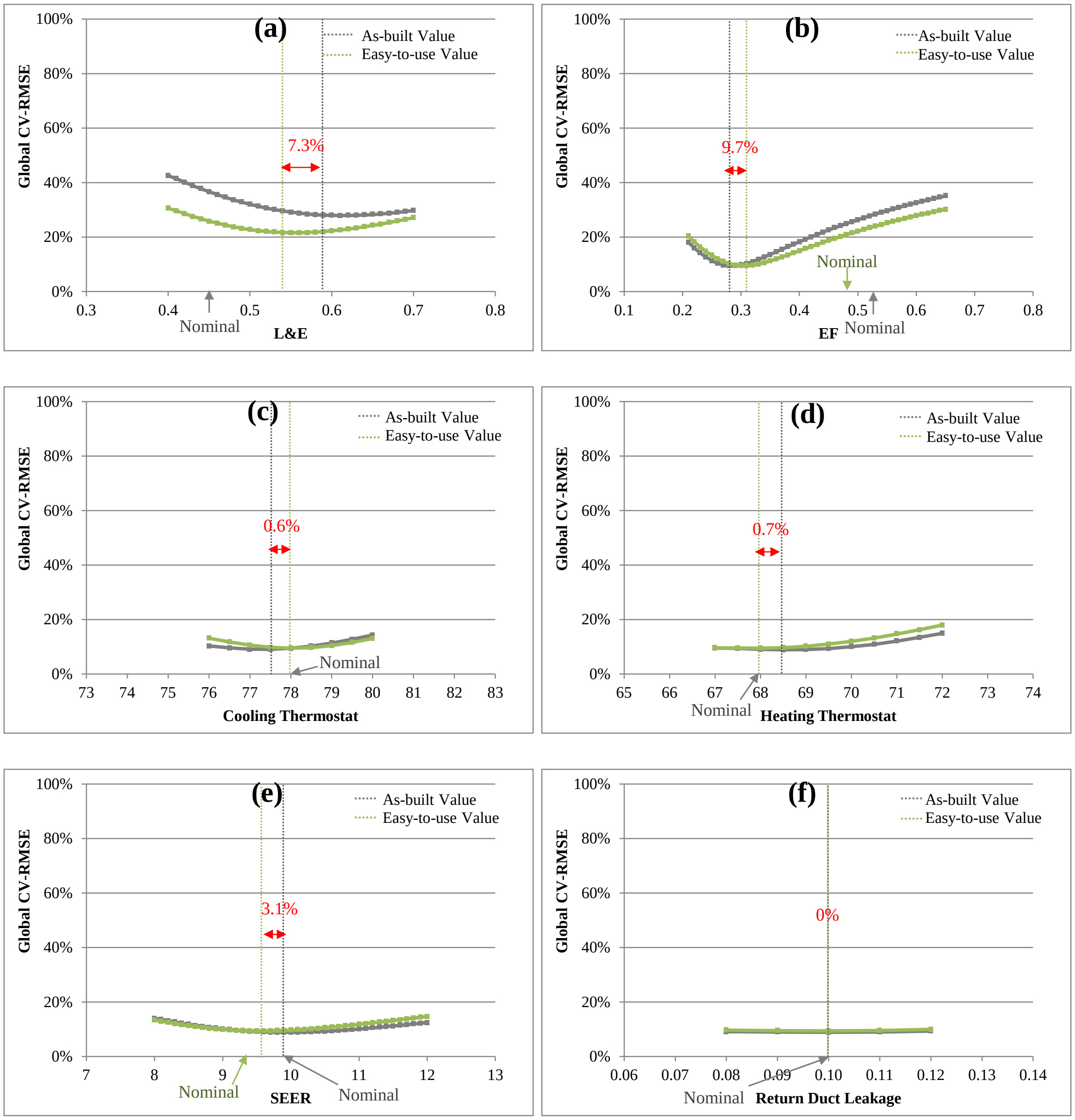


Figure 5.83 Each Calibrated Parameter Values and the Percent Differences for the Values Between the As-built and the Easy-to-use Simulation Models

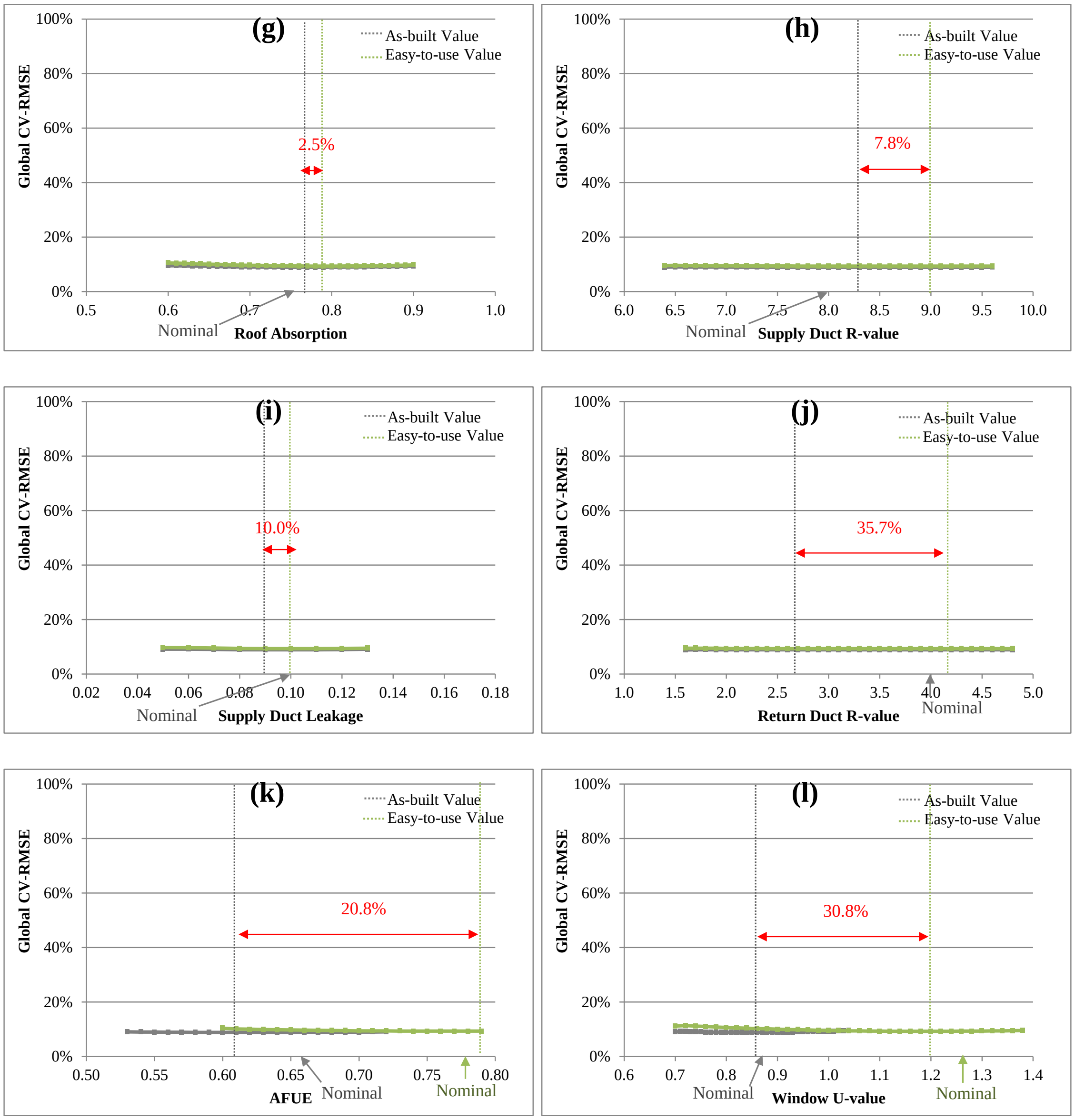


Figure 5.83 Continued

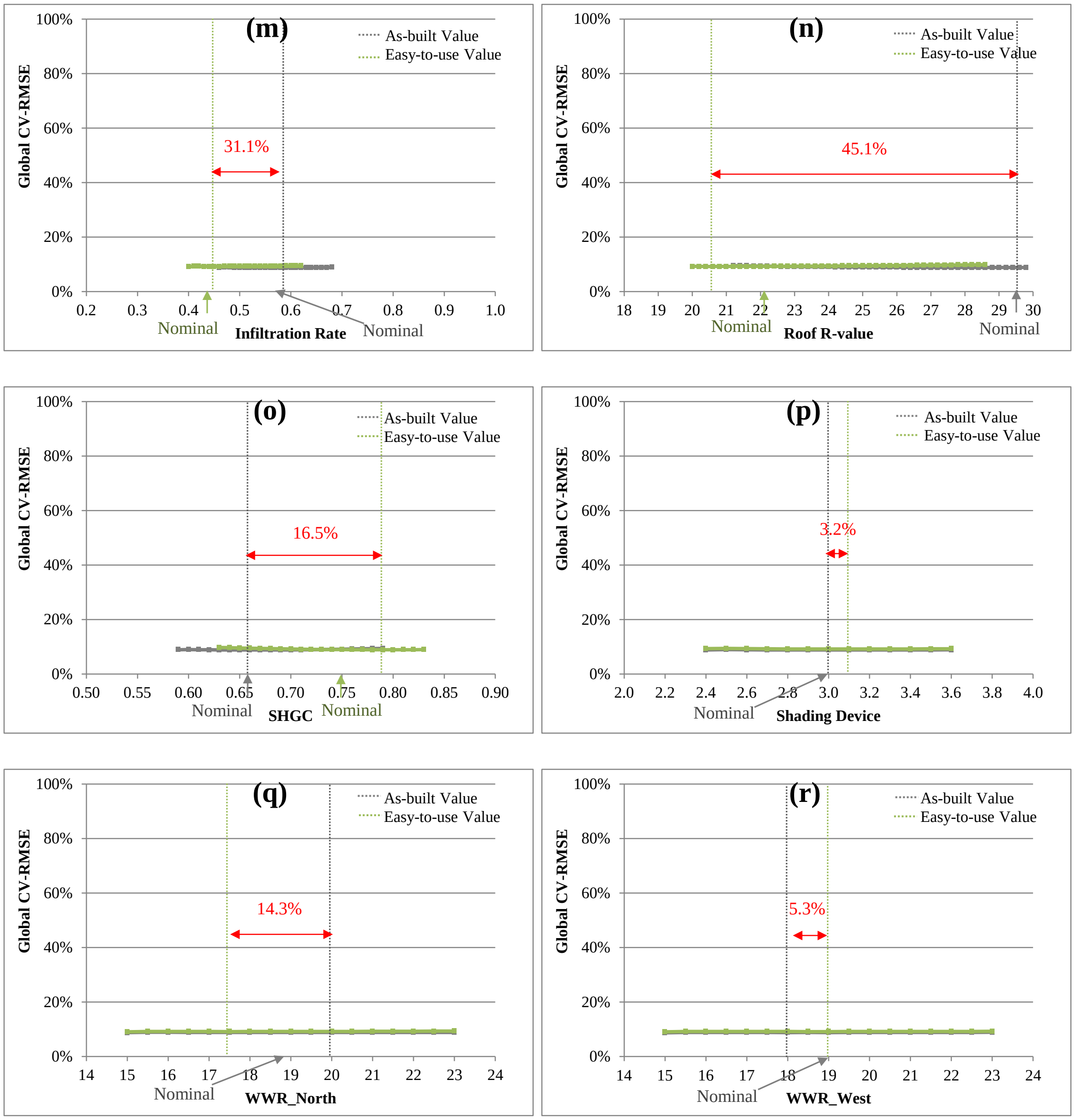


Figure 5.83 Continued

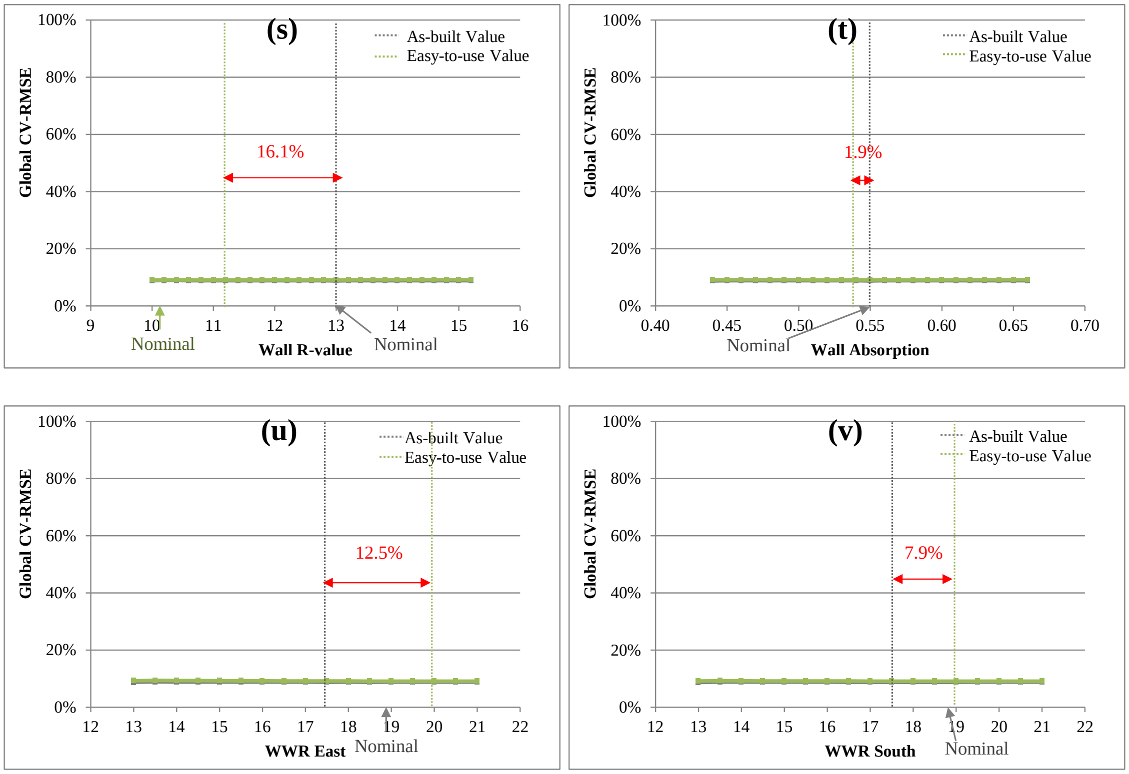


Figure 5.83 Continued

5.1.7 Determination of the Potential Energy Conservation Measures for Case-study House #1 using the As-built Calibrated Simulation

Using the as-built calibrated simulation model, the potential energy conservation measures (ECMs) for the case-study house #1 were evaluated, and annual energy savings and energy cost savings by the potential ECMs were calculated to estimate a simple pay-back period for the most energy efficient and cost effective ECMs.

To determine the potential ECMs, a standard house that is compliant with the 2009 IECC was modeled as described in Section 4.3.1, and the parameter values were compared with the calibrated simulation parameter values for the as-built simulation. In this comparison, the parameter values that have a large discrepancy more than 10% between the both models were used as candidates for the potential ECMs. Table 5.11 shows the comparison of the parameter values between the two models.

According to the 6th column of Table 5.11, the candidate parameters for the potential ECMs were EF, SEER, return duct leakage, supply duct leakage, return duct R-value, AFUE, Window U-value, infiltration rate, SHGC, shading device, WWR for west, wall absorption, WWR for east and south. Among these parameters, the candidates of the potential ECMs were narrowed down to EF, SEER, return duct leakage, supply duct leakage, return duct R-value, AFUE, window U-value, infiltration rate and SHGC as shown in the 7th column of Table 5.11, taking account of the applicability of ECM implementations. For example, the parameters such as shading device was excluded from the potential ECM even the percentage difference between the two models was above 10% because the standard house was modeled without shading device as a modeling assumption. Therefore, the candidates of the potential ECMs for the case-study house #1 was decided as improvement of the DHW efficiency, cooling system efficiency, duct leakage & R-value, heating system efficiency, glazing and infiltration, and the corresponding parameter values need to be above the values indicated in the 7th column of Table 5.11.

For the next step, the annual energy savings of the case-study house #1 from each ECM was simulated and compared to the actual annual energy use of the house. Table 5.12 shows the ECM parameter values for improvement of energy efficiency of the house. In order to find the most energy efficient and cost effective measures, the

Table 5.11 ECMs for the Case-study House #1 using the As-built Calibrated Simulation

3P Coefficient		Parameter	Calibrated As-built Simulation	A Standard House Simulation	% Difference	Improvement of Parameters	Potential ECM
Baseload	Elec.	L&E	0.59	0.58	2%		
	N.G.	EF	0.280	0.594	112%	**≥ 0.59**	**DHW**
Change-point	Elec.	Cooling Thermostat	77.5	75.0	3%		
	N.G.	Heating Thermostat	68.5	72.0	5%		
Slope	Elec.	SEER	9.90	13.00	31%	**≥ 13**	**Cooling System**
		Return Duct Leakage	0.100	0.056	44%	**≤ 0.056**	**Duct**
		Roof Absorption	0.77	0.75	3%		
		Supply Duct R-value	8.3	8.0	4%		
		Supply Duct Leakage	0.090	0.056	38%	**≤ 0.056**	**Duct**
		Return Duct R-value	2.7	6.0	122%	**≥ 6**	**Duct**
	N.G.	AFUE	0.61	0.78	28%	**≥ 0.78**	**Heating System**
		Window U-value	0.83	0.65	22%	**≤ 0.65**	**Glazing**
		Infiltration Rate	0.59	0.35	41%	**≤ 0.35**	**Infiltration**
		Roof R-value	29.6	27.84	6%		
		SHGC	0.66	0.30	55%	**≤ 0.3**	**Glazing**
		Shading Devices	3.0	0.0	100%		
		WWR North	20.0	20.8	4%		
		WWR West	18.0	20.8	16%		
		Wall R-value	13.0	11.8	9%		
		Wall Absorption	0.55	0.75	36%		
		WWR East	17.5	20.8	19%		
		WWR South	17.5	20.8	19%		

potential ECMs were put into four groups, which are: (1) for each ECM, (2) for a combination of envelope and fenestration ECMs, (3) for a combination of HVAC system ECMs and (4) for a combination of all ECMs.

Table 5.13 and Figure 5.84 show the annual energy savings, and Table 5.14 and Figure 5.85 show the annual energy cost savings from the implementation of all the ECMs. Negative total energy savings occurred for AFUE and return duct R-value because the annual energy use for the calibrated simulation was larger than actual annual energy use by 1.3%, which causes the negative energy savings in this case. This means that these ECMs are not energy efficient enough for the savings. Therefore, these ECMs were removed from the potential ECM list, and a new ECM list was simulated again. Table 5.15 and Figure 5.86 show the result of the new annual energy savings, and Table 5.16 and Figure 5.87 show the results of the new annual energy cost savings.

After that, a simple pay-back period for all ECMs was calculated based upon the cost information of unit and installation for all ECMs as shown in Table 5.17. The detail of the cost information for the unit and installation is shown in Appendix E. In these ECMs, the most energy efficient and cost effective ECMs were decided, which the simple pay-back period is less than 10 years. According to Table 5.17, the most energy efficient and cost effective ECMs were ECM 1 (i.e., EF measure) along with 4.0 years of pay-back period, ECM 3&4 (i.e., duct leakage measure) along with 3.4 years of pay-back period, ECM 6 (i.e., combination of EF and duct leakage measures) along with 4.0 years of pay-back period and ECM 7 (i.e., combination of EF, SEER and duct leakage measures) along with 7.7 years of pay-back period.

Table 5.12 ECM Parameter Values for the As-built Case-study House #1 Simulation

3P Coefficient		Parameter	Improvement of Parameter Values	Potential ECM
Baseload	Elec.	L&E		
	N.G.	EF	**0.590**	**DHW**
Change-point	Elec.	Cooling Thermostat		
	N.G.	Heating Thermostat		
Slope	Elec.	SEER	**13.00**	**Cooling System**
		Return Duct Leakage	**0.028**	**Duct**
		Roof Absorption		
		Supply Duct R-value		
		Supply Duct Leakage	**0.028**	**Duct**
		Return Duct R-value	**6**	**Duct**
	N.G.	AFUE	**0.78**	**Heating System**
		Window U-value	**0.40**	**Glazing**
		Infiltration Rate	**0.35**	**Infiltration**
		Roof R-value		
		SHGC	**0.25**	**Glazing**
		Shading Devices		
		WWR North		
		WWR West		
		Wall R-value		
		Wall Absorption		
		WWR East		
		WWR South		

Table 5.13 Annual Energy Savings from ECMs for House #1 using the As-built Calibrated Simulation

	ECM1	ECM2	ECM3	ECM4	ECM5	ECM6	ECM7	ECM8	ECM9	ECM10	ECM11	ECM12	Utility
	EF (0.28 → 0.59)	SEER (9.9 → 13.0)	AFUE (0.61 → 0.78)	Return Duct Leakage (0.100 → 0.028)	Return Duct R-value (2.7 → 6.0)	Supply Duct Leakage (0.090 → 0.028)	Infiltration Rate (0.59 → 0.35)	Window U-value (0.83 → 0.40)	SHGC (0.66 → 0.25)	Combination 1 (Envelope & Fenestration)	Combination 2 (HVAC Systems)	Combination 3 (All)	
Elec. Use (MMBtu)	69.7	62.8	69.7	65.4	69.2	67.7	69.1	70.6	63.0	62.8	57.7	53.1	69.9
N.G. Use (MMBtu)	21.2	40.0	39.1	39.8	40.0	39.8	38.9	36.9	42.1	37.0	19.6	17.6	38.4
Total Use (MMBtu)	90.9	102.9	108.8	105.2	109.2	107.5	108.0	107.5	105.1	99.8	77.3	70.6	108.4
Savings (MMBtu)	17.4	5.5	-0.4	3.2	-0.9	0.8	0.4	0.9	3.2	8.5	31.0	37.7	0.0
Total Savings (%)	19.2%	5.3%	-0.4%	3.0%	-0.8%	0.8%	0.3%	0.8%	3.1%	8.6%	40.2%	53.4%	0.0%

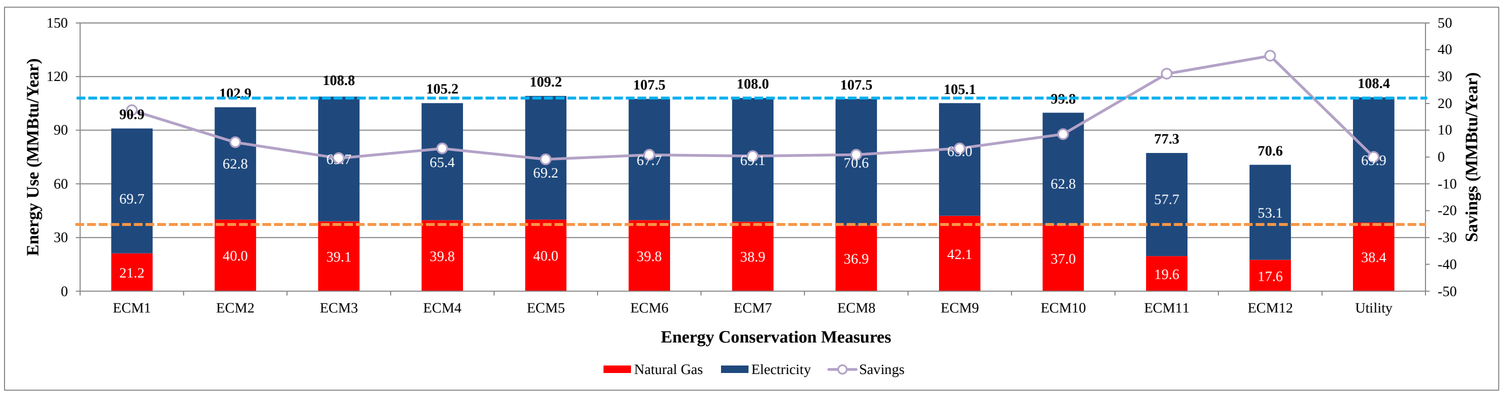


Figure 5.84 Annual Energy Savings from ECMs for House #1 using the As-built Calibrated Simulation

Table 5.14 Annual Energy Cost Savings from ECMs for House #1 using the As-built Calibrated Simulation

	ECM1	**ECM2**	**ECM3**	**ECM4**	**ECM5**	**ECM6**	**ECM7**	**ECM8**	**ECM9**	**ECM10**	**ECM11**	**ECM12**	**Utility**
	EF (0.28 → 0.59)	SEER (9.9 → 13.0)	AFUE (0.61 → 0.78)	Return Duct Leakage (0.100 → 0.028)	Return Duct R-value (2.7 → 6.0)	Supply Duct Leakage (0.090 → 0.028)	Infiltration Rate (0.59 → 0.35)	Window U-value (0.83 → 0.40)	SHGC (0.66 → 0.25)	Combination 1 (Envelope & Fenestration)	Combination 2 (HVAC Systems)	Combination 3 (All)	
Elec. Use ($/Year)	$ 2,283	$ 2,057	$ 2,283	$ 2,141	$ 2,266	$ 2,218	$ 2,261	$ 2,311	$ 2,063	$ 2,056	$ 1,888	$ 1,737	$ 2,289
N.G. Use ($/Year)	$ 271	$ 511	$ 499	$ 508	$ 511	$ 508	$ 497	$ 471	$ 537	$ 473	$ 251	$ 224	$ 491
Total Use ($/Year)	$ 2,554	$ 2,568	$ 2,782	$ 2,649	$ 2,777	$ 2,725	$ 2,758	$ 2,783	$ 2,601	$ 2,529	$ 2,139	$ 1,962	$ 2,780
Savings ($/Year)	$ 226	$ 211	$ (2)	$ 131	$ 3	$ 54	$ 21	$ (3)	$ 179	$ 251	$ 641	$ 818	$ -
Total Savings (%)	8.8%	8.2%	-0.1%	5.0%	0.1%	2.0%	0.8%	-0.1%	6.9%	9.9%	30.0%	41.7%	0.0%

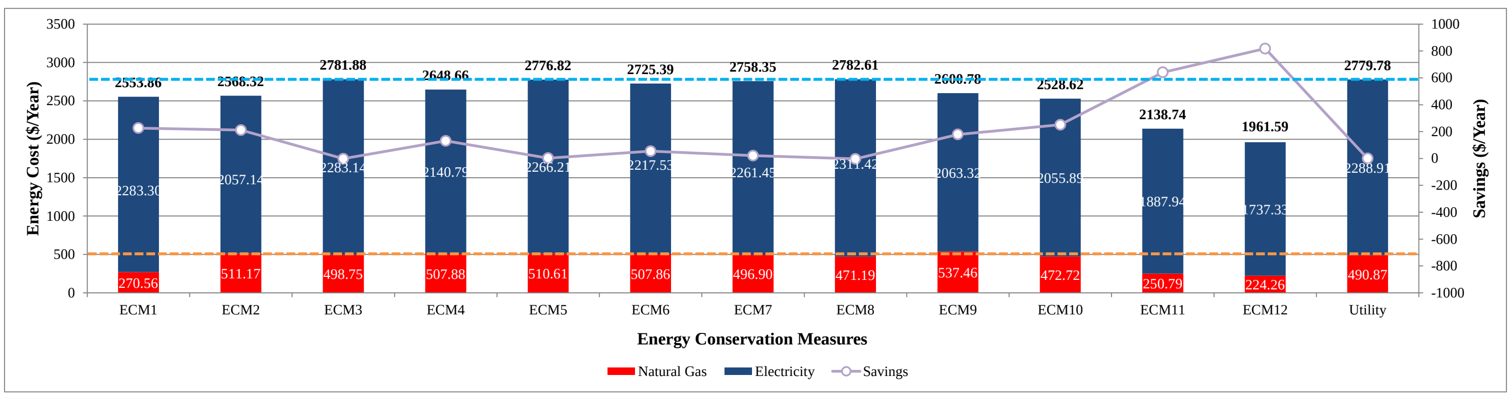


Figure 5.85 Annual Energy Cost Savings from ECMs for House 31 using the As-built Calibrated Simulation

Table 5.15 Annual Energy Savings from New ECMs for House #1 using the As-built Calibrated Simulation

	ECM1	ECM2	ECM3	ECM4	ECM5	ECM6	ECM7	ECM8	Utility
	EF (0.28 → 0.59)	SEER (9.9 → 13.0)	Return Duct Leakage (0.100 → 0.028)	Supply Duct Leakage (0.100 → 0.028)	SHGC (0.66 → 0.25)	Combination 1 (EF and Duct Leakage)	Combination 2 (HVAC Systems)	Combination 3 (All)	
Elec. Use (MMBtu)	69.7	62.8	65.4	67.7	63.0	63.7	58.0	53.5	69.9
N.G. Use (MMBtu)	21.2	40.0	39.8	39.8	42.1	20.5	20.5	22.4	38.4
Total Use (MMBtu)	90.9	102.9	105.2	107.5	105.1	84.2	78.5	75.9	108.4
Savings (MMBtu)	17.4	5.5	3.2	0.8	3.2	24.2	29.9	32.5	0.0
Total Savings (%)	19.2%	5.3%	3.0%	0.8%	3.1%	28.7%	38.1%	42.9%	0.0%

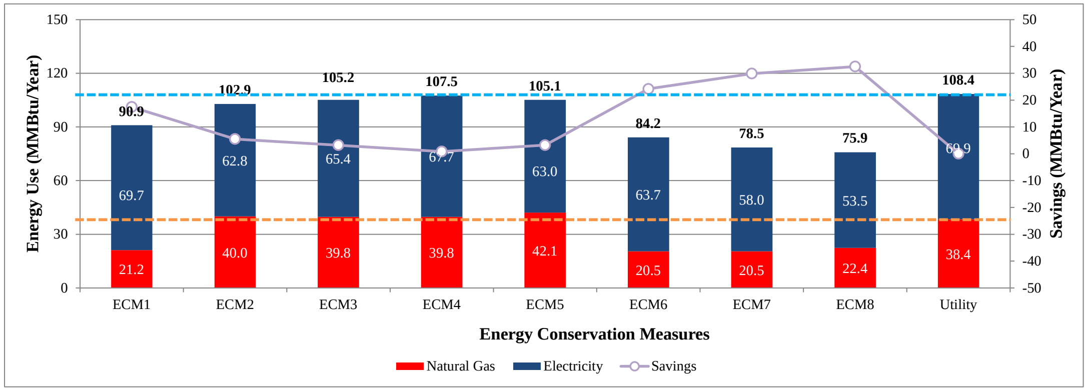


Figure 5.86 Annual Energy Savings from New ECMs for House #1 using the As-built Calibrated Simulation

Table 5.16 Annual Energy Cost Savings from New ECMs for House #1 using the As-built Calibrated Simulation

	ECM1	ECM2	ECM3	ECM4	ECM5	ECM6	ECM7	ECM8	Utility
	EF (0.28 → 0.59)	SEER (9.9 → 13.0)	Return Duct Leakage (0.100 → 0.028)	Supply Duct Leakage (0.100 → 0.028)	SHGC (0.66 → 0.25)	Combination 1 (EF and Duct Leakage)	Combination 2 (HVAC Systems)	Combination 3 (All)	
Elec. Use ($/Year)	$ 2,283	$ 2,057	$ 2,141	$ 2,218	$ 2,063	$ 2,084	$ 1,897	$ 1,751	$ 2,289
N.G. Use ($/Year)	$ 271	$ 511	$ 508	$ 508	$ 537	$ 262	$ 262	$ 286	$ 491
Total Use ($/Year)	$ 2,554	$ 2,568	$ 2,649	$ 2,725	$ 2,601	$ 2,346	$ 2,159	$ 2,036	$ 2,780
Savings ($/Year)	$ 226	$ 211	$ 131	$ 54	$ 179	$ 434	$ 620	$ 743	$ -
Total Savings (%)	8.8%	8.2%	5.0%	2.0%	6.9%	18.5%	28.7%	36.5%	0.0%

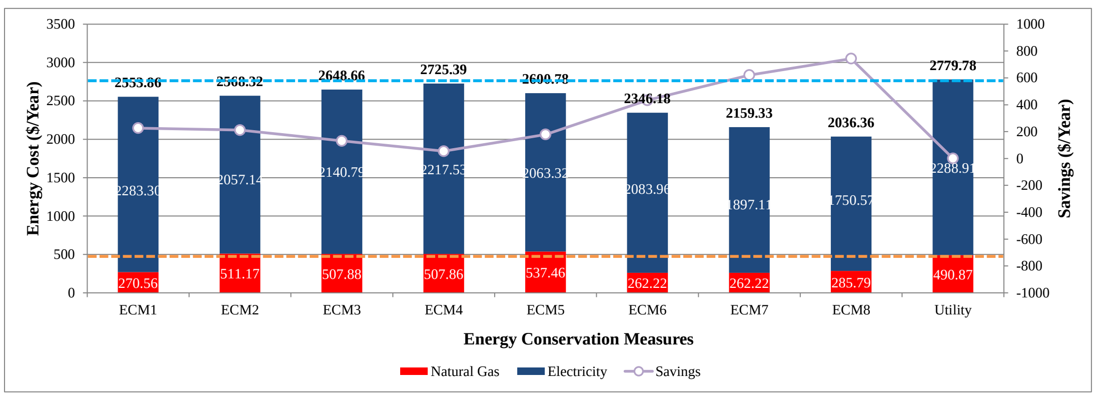


Figure 5.87 Annual Energy Cost Savings from New ECMs for House #1 using the As-built Calibrated Simulation

Table 5.17 Result of Simple Pay-back Period Calculation from New ECMs using the As-built House #1 Calibrated Simulation

Component Description		Unit	Unit Cost[1] [$]	Estimated Cost [$]	Annual Energy Savings [$]	Estimated Payback [yrs]
ECM 1						
Hot Water Heater[3] (50 gallon / 40000 Btu/hr)	EF 0.63	$/Unit	$ 1,100	$ 1,100	$ 226	**4.9**
ECM 2						
Space Cooling Equipment[3] (5 tons)	SEER 13	$/Unit	$ 3,030	$ 3,030	$ 211	**14.3**
ECM 3 &4						
Improved Duct Sealing[2]		$/ft^2	$ 0.13	$ 622	$ 186	**3.4**
ECM 5						
Fenestration	SHGC-0.25	$/ft^2	$ 31.77	$ 9,346	$ 179	**52.2**
ECM 6						
Combination 1 (ECM 1, 3 and 4)				$ 1,722	$ 434	**4.0**
ECM 7						
Combination 2 (ECM 1, 2, 3 and 4)				$ 4,752	$ 620	**7.7**
ECM 8						
Combination 3 (ECM 1, 2, 3, 4 and 5)				$ 14,097	$ 743	**19.0**

Notes:
1. Costs inclusive of labor and equipment.
2. Incremental costs.
3. Assuming no charge for installation costs.

5.1.8 Determination of the Potential Energy Conservation Measures for Case-study House #1 using the Easy-to-use Calibrated Simulation

In a similar fashion to the determination of the potential ECMs for the case-study house #1 using the as-built calibrated simulation, the potential ECMs for the case-study house #1 were determined as well using the easy-to-use calibrated simulation model, including calculation of the annual energy savings and energy cost savings by the potential ECMs as well as simple pay-backs for the most energy efficient and cost effective ECMs.

To determine the potential ECMs, a standard house was modeled, and the parameter values were compared with the calibrated simulation parameter values for the easy-to-use simulation. In this comparison, the candidates of the potential ECMs were decided as shown in 7th column of Table 5.18, which are EF, SEER, return duct leakage, supply duct leakage, return duct R-value, AFUE, window U-value, infiltration rate, roof R-value and SHGC.

For the next step, the annual energy savings of the case-study house #1 from each ECM was simulated and compared to the actual annual energy use of the house. Table 5.19 shows the ECM parameter values for improvement of energy efficiency of the house. In order to find the most cost effective measures, the potential ECMs were grouped by four, which are: (1) for each ECM, (2) for a combination of envelope and fenestration ECMs, (3) for a combination of HVAC system ECMs and (4) for a combination of all ECMs.

Table 5.18 ECMs for the Case-study House #1 using the Easy-to-use Calibrated Simulation

3P Coefficient		Parameter	Calibrated Easy-to-use Simulation	A Standard House Simulation	% Difference	Improvement of Parameters	Potential ECM
Baseload	Elec.	L&E	0.55	0.58	5%		
	N.G.	EF	0.310	0.594	92%	**≥ 0.59**	**DHW**
Change-point	Elec.	Cooling Thermostat	78.0	75.0	4%		
	N.G.	Heating Thermostat	68	72.0	6%		
Slope	Elec.	SEER	9.60	13.00	35%	**≥ 13**	**Cooling System**
		Return Duct Leakage	0.100	0.056	44%	**≤ 0.056**	**Duct**
		Roof Absorption	0.79	0.75	5%		
		Supply Duct R-value	9	8.0	10%		
		Supply Duct Leakage	0.100	0.056	44%	**≤ 0.056**	**Duct**
		Return Duct R-value	4.2	6.0	43%	**≥ 6**	**Duct**
	N.G.	AFUE	0.77	0.78	1%	**≥ 0.78**	**Heating System**
		Window U-value	1.20	0.65	46%	**≤ 0.65**	**Glazing**
		Infiltration Rate	0.45	0.35	22%	**≤ 0.35**	**Infiltration**
		Roof R-value	20.40	27.84	36%	**≥ 27.84**	**Roof Insulation**
		SHGC	0.79	0.30	62%	**≤ 0.3**	**Glazing**
		Shading Devices	3.1	0.0	100%		
		WWR North	17.5	20.8	19%		
		WWR West	19	20.8	9%		
		Wall R-value	11.2	11.8	5%		
		Wall Absorption	0.54	0.75	39%		
		WWR East	20	20.8	4%		
		WWR South	19.0	20.8	9%		

Table 5.22 and Figure 5.90 show the annual energy savings, and Table 5.23 and Figure 5.91 show the final annual energy cost savings from the implementation of all the ECMs. After that, the simple pay-back period for all ECMs was calculated based upon the cost information of unit and installation for all ECMs as shown in Table 5.24. The detail of the cost information for the unit and installation is shown in Appendix E. In these ECMs, the most energy efficient and cost effective ECMs were decided in which the simple pay-back period is less than 10 years. According to Table 5.24, the most energy efficient and cost effective ECMs were ECM 1(i.e., EF measure) along with a 4.9

year pay-back period, ECM 3&4 (duct leakage measure) along with a 2.1 year pay-back period, ECM 7 (i.e., combination of EF and duct leakage measures) along with a 3.8 year pay-back period and ECM 9 (combination of EF, SEER, duct leakage measures) along with a 7.1 year pay-back period.

Table 5.19 ECM Parameter Values for the Easy-to-use Case-study House #1 Simulation

3P Coefficient		Parameter	Improvement of Parameter Values	Potential ECM
Baseload	Elec.	L&E		
	N.G.	EF	**0.590**	**DHW**
Change-point	Elec.	Cooling Thermostat		
	N.G.	Heating Thermostat		
Slope	Elec.	SEER	**13.00**	**Cooling System**
		Return Duct Leakage	**0.028**	**Duct**
		Roof Absorption		
		Supply Duct R-value		
		Supply Duct Leakage	**0.028**	**Duct**
		Return Duct R-value	**6**	**Duct**
	N.G.	AFUE	**0.78**	**Heating System**
		Window U-value	**0.40**	**Glazing**
		Infiltration Rate	**0.35**	**Infiltration**
		Roof R-value	**38**	**Roof Insulation**
		SHGC	**0.25**	**Glazing**
		Shading Devices		
		WWR North		
		WWR West		
		Wall R-value		
		Wall Absorption		
		WWR East		
		WWR South		

Table 5.20 Annual Energy Savings from ECMs for House #1 using the Easy-to-use Calibrated Simulation

	ECM1	ECM2	ECM3	ECM4	ECM5	ECM6	ECM7	ECM8	ECM9	ECM10	ECM11	ECM12	ECM13	Utility
	EF (0.31 → 0.59)	SEER (9.6 → 13.0)	AFUE (0.77→ 0.78)	Return Duct Leakage (0.100 → 0.028)	Return Duct R-value (4.2 → 6.0)	Supply Duct Leakage (0.100 → 0.028)	Infiltration Rate (0.45 → 0.35)	Window U-value (1.20 → 0.40)	SHGC (0.79 → 0.25)	Roof R-value (20.4 → 38.0)	Combination 1 (Envelope & Fenestration)	Combination 2 (HVAC Systems)	Combination 3 (All)	
Elec. Use (MMBtu)	69.4	61.4	69.4	64.7	69.2	67.0	69.1	70.9	60.7	66.9	58.4	55.9	48.9	69.9
N.G. Use (MMBtu)	22.3	37.7	37.6	37.4	37.6	37.3	37.3	33.3	40.3	36.1	33.0	21.4	17.4	38.4
Total Use (MMBtu)	91.7	99.0	107.0	102.0	106.9	104.2	106.4	104.2	101.0	103.0	91.4	77.3	66.3	108.4
Savings (MMBtu)	16.6	9.3	1.4	6.3	1.5	4.1	2.0	4.2	7.4	5.4	17.0	31.1	42.1	0.0
Total Savings (%)	18.1%	9.4%	1.3%	6.2%	1.4%	4.0%	1.8%	4.0%	7.3%	5.2%	18.6%	40.2%	63.5%	0.0%

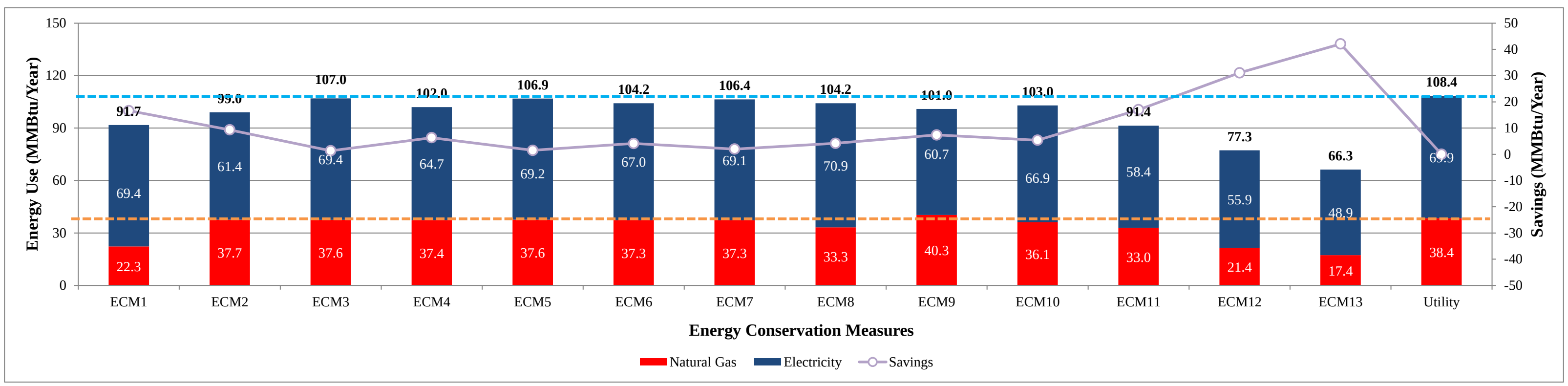


Figure 5.88 Annual Energy Savings from ECMs for House #1 using the Easy-to-use Calibrated Simulation

Table 5.21 Annual Energy Cost Savings from ECMs for House #1 using the Easy-to-use Calibrated Simulation

	ECM1	ECM2	ECM3	ECM4	ECM5	ECM6	ECM7	ECM8	ECM9	ECM10	ECM11	ECM12	ECM13	Utility
	EF (0.31 → 0.59)	SEER (9.6 → 13.0)	AFUE (0.77→ 0.78)	Return Duct Leakage (0.100 → 0.028)	Return Duct R-value (4.2 → 6.0)	Supply Duct Leakage (0.100 → 0.028)	Infiltration Rate (0.45 → 0.35)	Window U-value (1.20 → 0.40)	SHGC (0.79 → 0.25)	Roof R-value (20.4 → 38.0)	Combination 1 (Envelope & Fenestration)	Combination 2 (HVAC Systems)	Combination 3 (All)	
Elec. Use ($/Year)	$ 2,273	$ 2,009	$ 2,273	$ 2,117	$ 2,266	$ 2,192	$ 2,263	$ 2,321	$ 1,987	$ 2,191	$ 1,912	$ 1,829	$ 1,602	$ 2,289
N.G. Use ($/Year)	$ 285	$ 481	$ 480	$ 477	$ 481	$ 476	$ 476	$ 425	$ 515	$ 461	$ 421	$ 274	$ 222	$ 491
Total Use ($/Year)	$ 2,557	$ 2,490	$ 2,753	$ 2,594	$ 2,747	$ 2,668	$ 2,739	$ 2,746	$ 2,501	$ 2,651	$ 2,333	$ 2,103	$ 1,823	$ 2,780
Savings ($/Year)	$ 222	$ 290	$ 27	$ 185	$ 33	$ 112	$ 41	$ 34	$ 279	$ 129	$ 447	$ 677	$ 956	$ -
Total Savings (%)	8.7%	11.6%	1.0%	7.1%	1.2%	4.2%	1.5%	1.2%	11.1%	4.9%	19.2%	32.2%	52.5%	0.0%

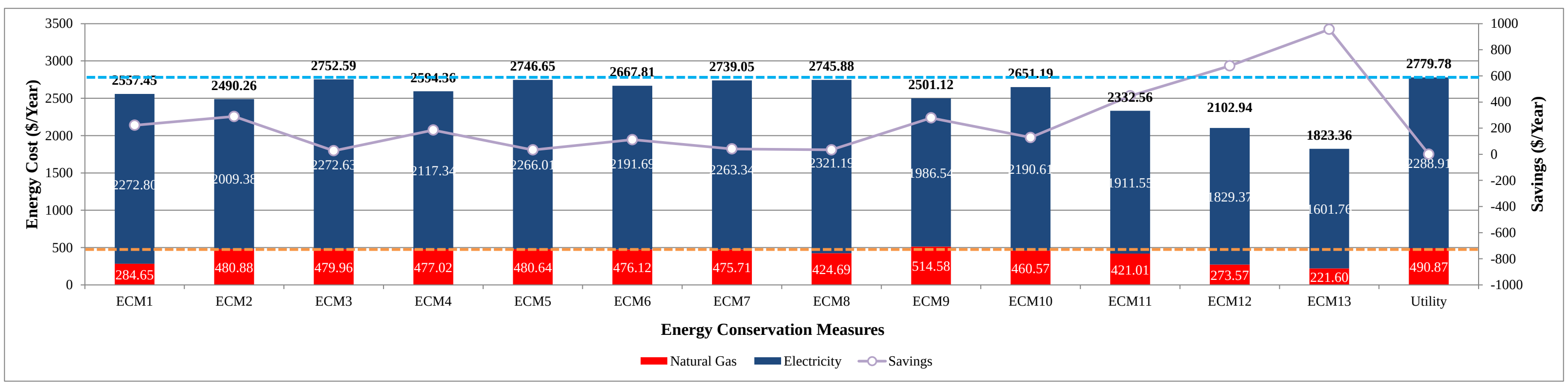


Figure 5.89 Annual Energy Cost Savings from ECMs for House #1 using the Easy-to-use Calibrated Simulation

Table 5.22 Annual Energy Savings from New ECMs for House #1 using the Easy-to-use Calibrated Simulation

	ECM1	ECM2	ECM3	ECM4	ECM5	ECM6	ECM7	ECM8	ECM9	Utility
	EF (0.31 → 0.59)	SEER (9.6 → 13.0)	Return Duct Leakage (0.100 → 0.028)	Supply Duct Leakage (0.100 → 0.028)	SHGC (0.79 → 0.25)	Roof R-value (20.4 → 38.0)	Combination 1 (EF & Duct Leakage)	Combination 2 (HVAC Systems)	Combination 3 (All)	
Elec. Use (MMBtu)	69.4	61.4	64.7	67.0	60.7	66.9	62.5	56.0	48.7	69.9
N.G. Use (MMBtu)	22.3	37.7	37.4	37.3	40.3	36.1	21.5	21.5	22.2	38.4
Total Use (MMBtu)	91.7	99.0	102.0	104.2	101.0	103.0	84.0	77.5	70.9	108.4
Savings (MMBtu)	16.6	9.3	6.3	4.1	7.4	5.4	24.3	30.9	37.4	0.0
Total Savings (%)	18.1%	9.4%	6.2%	4.0%	7.3%	5.2%	28.9%	39.8%	52.8%	0.0%

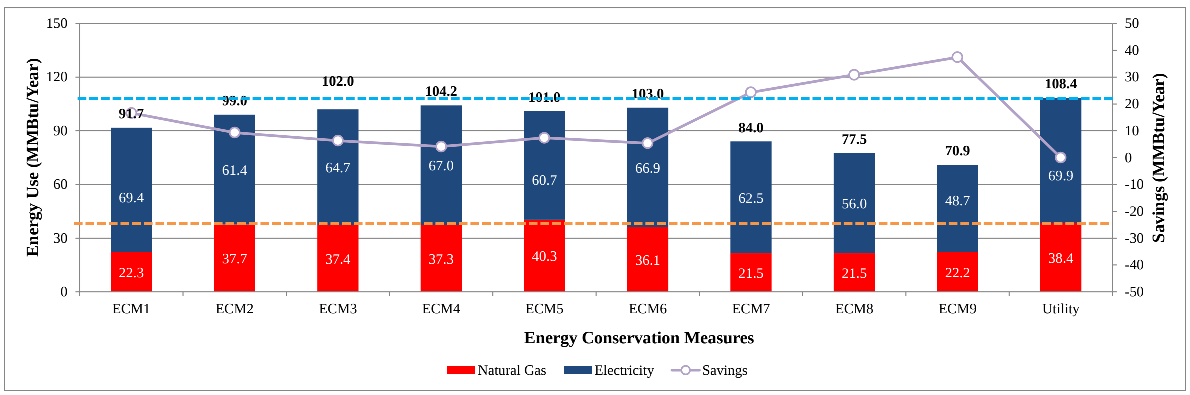


Figure 5.90 Annual Energy Savings from New ECMs for House #1 using the Easy-to-use Calibrated Simulation

Table 5.23 *Annual Energy Cost Savings from New ECMs for House #1 using the Easy-to-use Calibrated Simulation*

	ECM1	ECM2	ECM3	ECM4	ECM5	ECM6	ECM7	ECM8	ECM9	Utility
	EF (0.31 → 0.59)	SEER (9.6 → 13.0)	Return Duct Leakage (0.100 → 0.028)	Supply Duct Leakage (0.100 → 0.028)	SHGC (0.79 → 0.25)	Roof R-value (20.4 → 38.0)	Combination 1 (EF & Duct Leakage)	Combination 2 (HVAC Systems)	Combination 3 (All)	
Elec. Use ($/Year)	$ 2,273	$ 2,009	$ 2,117	$ 2,192	$ 1,987	$ 2,191	$ 2,047	$ 1,833	$ 1,595	$ 2,289
N.G. Use ($/Year)	$ 285	$ 481	$ 477	$ 476	$ 515	$ 461	$ 275	$ 275	$ 284	$ 491
Total Use ($/Year)	$ 2,557	$ 2,490	$ 2,594	$ 2,668	$ 2,501	$ 2,651	$ 2,322	$ 2,107	$ 1,879	$ 2,780
Savings ($/Year)	$ 222	$ 290	$ 185	$ 112	$ 279	$ 129	$ 458	$ 672	$ 901	$ -
Total Savings (%)	8.7%	11.6%	7.1%	4.2%	11.1%	4.9%	19.7%	31.9%	48.0%	0.0%

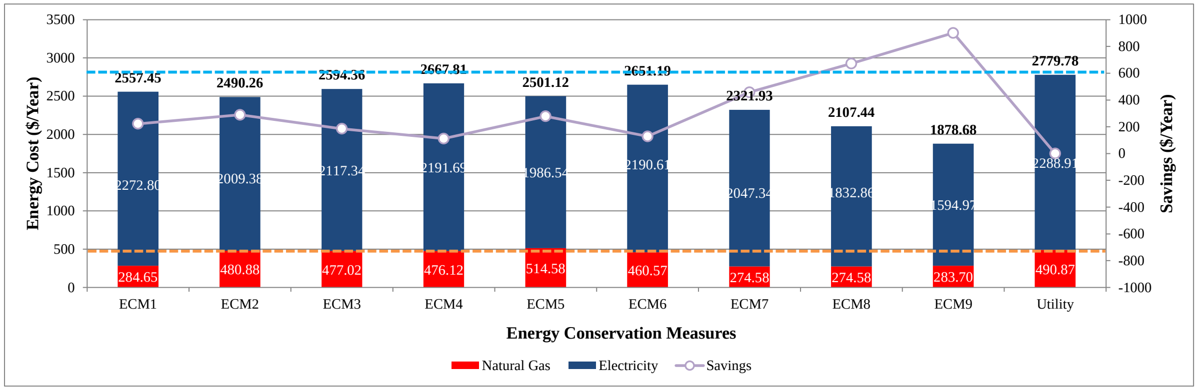


Figure 5.91 *Annual Energy Cost Savings from New ECMs for House #1 using the Easy-to-use Calibrated Simulation*

Table 5.24 Result of Simple Pay-back Period Calculation from New ECMs for House #1 using the Easy-to-use Calibrated Simulation

Compenent Description		Unit	Unit Cost[1] [$]	Estimated Cost [$]	Annual Energy Savings [$]	Estimated Payback [yrs]
ECM 1						
Hot Water Heater[3] (50 gallon / 40000 Btu/hr)	EF 0.63	$/Unit	$ 1,100	$ 1,100	$ 222	**4.9**
ECM 2						
Space Cooling Equipment[3] (5 tons)	SEER 13	$/Unit	$ 3,030	$ 3,030	$ 290	**10.5**
ECM 3 & 4						
Improved Duct Sealing[2]		$/ft^2	$ 0.13	$ 622	$ 297	**2.1**
ECM 5						
Fenestration	SHGC-0.25	$/ft^2	$ 31.77	$ 9,346	$ 279	**33.5**
ECM 6						
Roof Blown-in Insulation	R-38	$/ft2	$ 1.33	$ 3,180	$ 129	**24.7**
ECM 7						
Combination 1 (ECM 1, 3 and 4)				$ 1,722	$ 458	**3.8**
ECM 8						
Combination 2 (ECM 1, 2, 3 and 4)				$ 4,752	$ 672	**7.1**
ECM 9						
Combination 3 (ECM 1, 2, 3, 4, 5 and 6)				$ 17,277	$ 901	**19.2**

Notes:

1. Costs inclusive of labor and equipment.
2. Incremental costs.
3. Assuming no charge for installation costs.

5.1.9 Comparison Results of the Determination of the Potential Energy Conservation Measures (ECMs) for the As-built and Easy-to-use Case-study House #1 Simulation

Through Section 5.1.7 and 5.1.8, the most energy efficient and cost effective potential ECMs from the as-built and the easy-to-use simulations were decided using a simple pay-back period calculation, which is less than 10 years. The potential ECMs from the both simulations (i.e., the as-built and the easy-to-use simulations) were: EF measure, duct leakage measure, a combination of EF and duct leakage measures and a combination of EF, SEER and duct leakage measures.

The simple pay-back period for the EF measure was 4.9 year from the as-built simulation and 4.9 year from the easy-to-use simulation; for the duct leakage measure was 3.4 year from the as-built simulation and 2.1 year from the easy-to-use simulation; for the combination of EF and duct leakage measures was 4.0 year from the as-built simulation and 3.8 year from the easy-to-use simulation; for the combination of EF, SEER and duct leakage measures was 7.7 year from the as-built simulation and 7.1 year from the easy-to-use simulation.

This result shows that the easy-to-use calibrated simulation brought the same ECMs as the as-built calibrated simulation, and the pay-back period for each ECM from the both simulations was also close to each other. Therefore, the easy-to-use simulation can be used for home energy audit methodology as the as-built simulation. In order to verify the methodology works well, it was applied to two more houses located in College Station and Plano, Texas as seen in the next two sections.

5.2 Description of Case-study House #2

Case-study house #2 is a single-family house located in College Station, Texas, which was built in 2002. The basic information of the building for the easy-to-use simulation (i.e., constructed year and location of the house) and photos were obtained from the homeowner. Figure 5.92 through Figure 5.95 shows the case-study house taken from different points of view. The annual monthly utility bills for electricity and natural gas use during 2012 and 2013 were also obtained from the homeowner to use as measured energy use for the calibration. Table 5.25 and Table 5.26 shows the monthly electricity and natural gas utility billing data, and calculated monthly average daily use, respectively.

In a similar fashion to case-study house #1, the IRB approval for this case-study house for the research compliance and biosafety's human subject's protection program was obtained and is attached in Figure A.1 in Appendix A.

The easy-to-use simulation was developed using the DDP, which is based on the building characteristics information shown in Table 4.3. The occupancy, lighting and equipment, and HVAC operating schedules were set to be run 24 hours per a day for the whole year, and the building geometry was simplified using the inputs for the DDP. The easy-to-use simulation was run using a TRY formatted weather file with measured weather data for College Station, Texas (Figure D.2 and D.3 in Appendix D). Hourly and average daily electricity and natural gas use was extracted from the hourly-report of the simulation output file. Figure 5.96 shows monthly average daily plots for the simulated and measured electricity and natural gas use against outdoor temperature, and

Figure 5.97 shows the same energy use and their 3PC and 3PH regression models that were performed using the IMT. A monthly CV (RMSE) for the easy-to-use simulation was calculated as 40.7% for the electricity use, 64.9% for the natural gas use and 47.8% for global, respectively.

Figure 5.92 Front View (Northwest) of the Case-study House #2

Figure 5.93 Back View (Southeast) of the Case-study House #2

Figure 5.94 Side View (Southwest) of the Case-study House #2

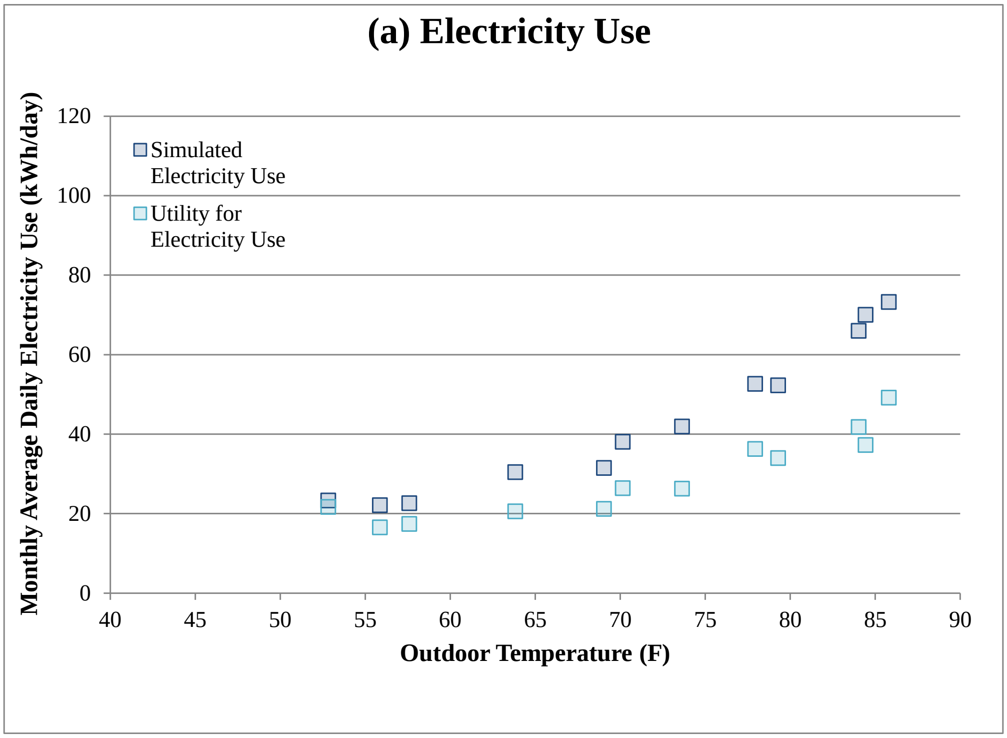
Figure 5.95 Side View (Northeast) of the Case-study House #2

Table 5.25 Monthly Electricity Utility Billing Data for the Case-study House #2

Billing Period		Days in Billing Periods	Monthly Electricity Use (kWh)	Calculated Monthly Avg. Daily Elec. Use (kWh/Day)
Start Date	End Date			
3/6/2012	4/4/2012	30	635	21.2
4/5/2012	5/3/2012	29	761	26.2
5/4/2012	6/6/2012	34	1154	33.9
6/7/2012	7/5/2012	29	1212	41.8
7/6/2012	8/6/2012	32	1192	37.3
8/7/2012	9/6/2012	31	1524	49.2
9/7/2012	10/4/2012	28	1015	36.3
10/5/2012	11/2/2012	29	765	26.4
11/3/2012	12/5/2012	33	678	20.5
12/6/2012	1/8/2013	34	737	21.7
1/9/2013	2/6/2013	29	505	17.4
2/7/2013	3/5/2013	27	446	16.5

Table 5.26 Monthly Natural Gas Utility Billing Data for the Case-study House #2

Billing Period		Days in Billing Periods	Monthly N.G. Use (MCF)	Monthly N.G. Use (MMBtu)	Calculated Monthly Avg. Daily N.G. Use (MMBtu/Day)
Start Date	End Date				
3/24/2012	4/24/2012	32	1.6	1.6	0.050
4/25/2012	5/23/2012	29	1.0	1.0	0.034
5/24/2012	6/22/2012	30	1.5	1.5	0.050
6/23/2012	7/25/2012	33	1.1	1.1	0.033
7/26/2012	8/24/2012	30	0.6	0.6	0.020
8/25/2012	9/25/2012	32	1.0	1.0	0.031
9/26/2012	10/24/2012	29	1.3	1.3	0.045
10/25/2012	11/26/2012	33	2.4	2.4	0.073
11/27/2012	12/21/2012	25	3.2	3.2	0.128
12/22/2012	1/23/2013	33	10.1	10.1	0.306
1/24/2013	2/22/2013	30	3.6	3.6	0.120
2/23/2013	3/21/2013	27	3.7	3.7	0.137



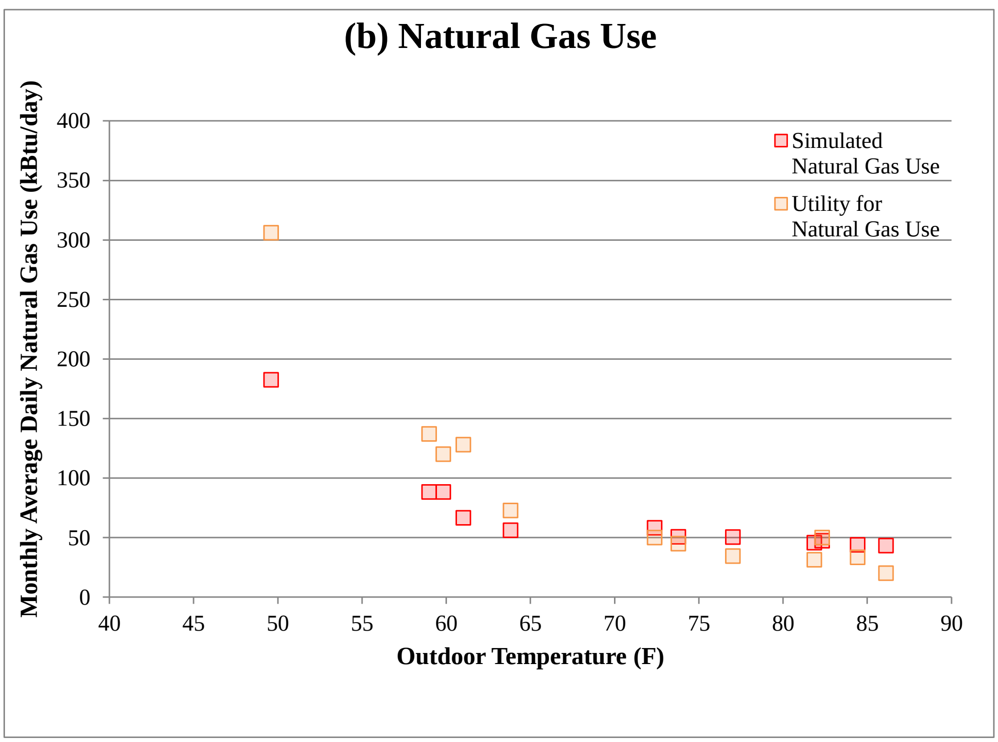
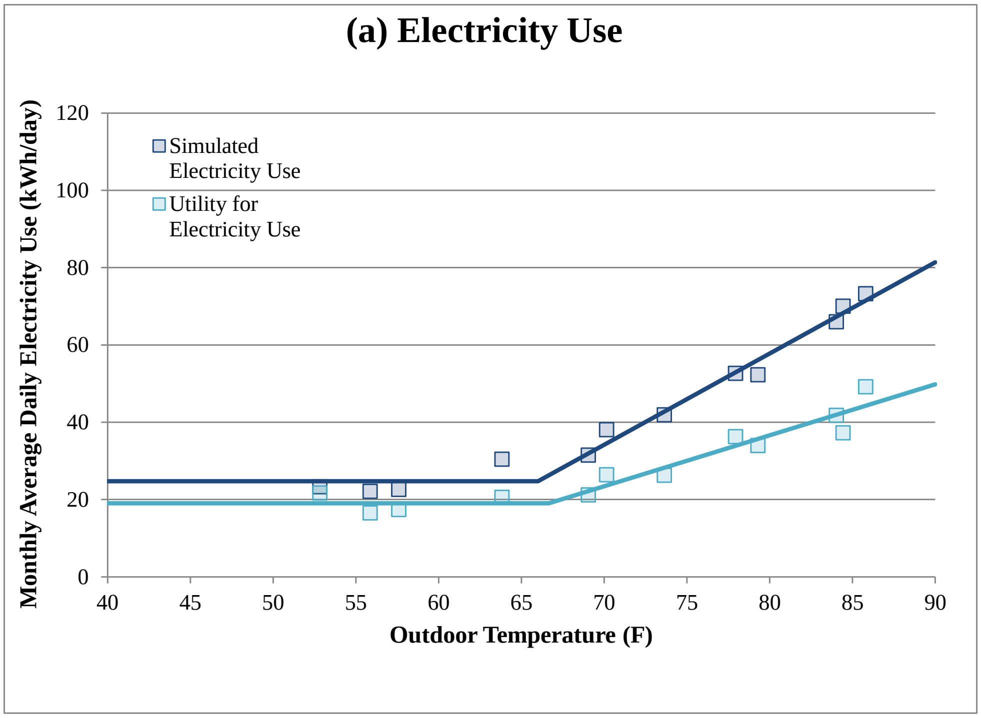


Figure 5.96 Results for the Easy-to-use House #2 Simulation and the Monthly Utility Bills for: (a) Electricity Use and (b) Natural Gas Use



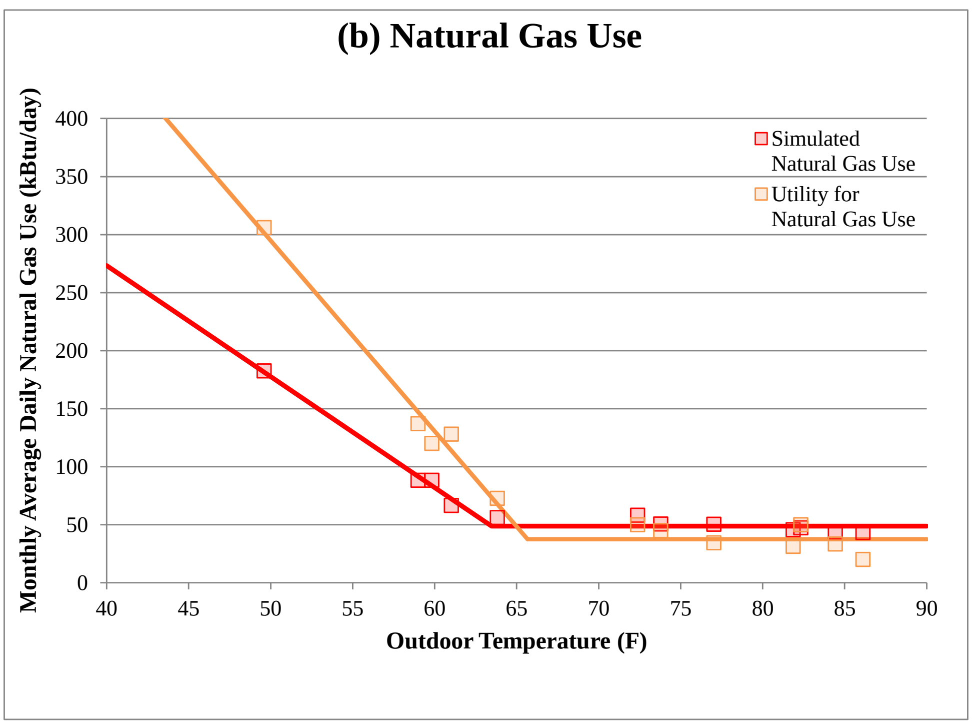
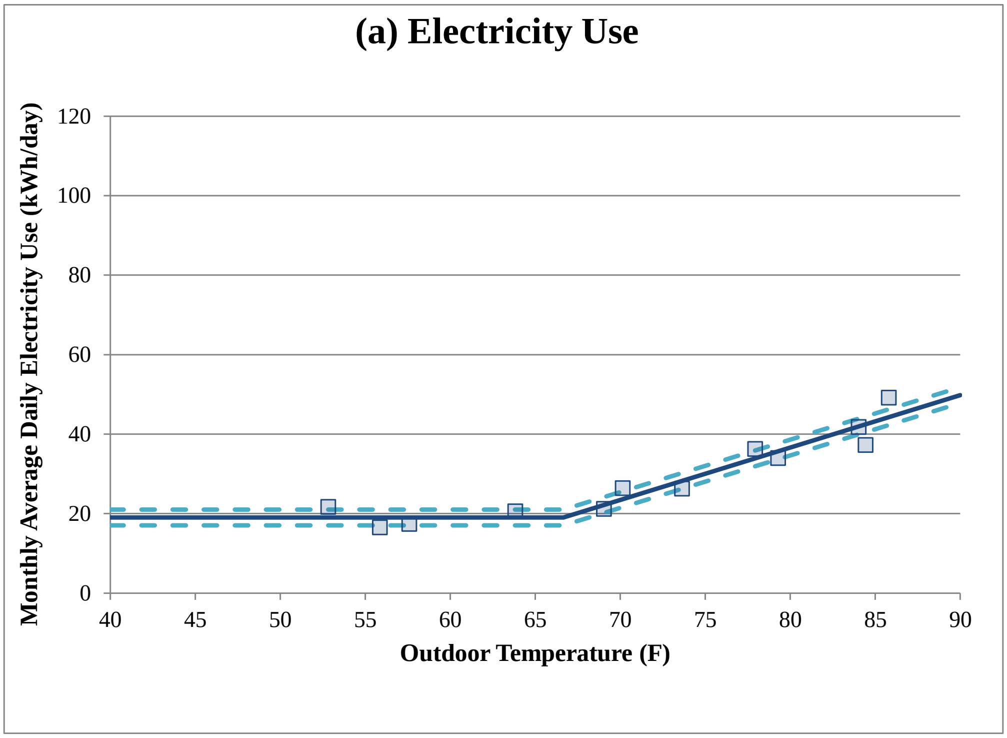


Figure 5.97 Results for the Easy-to-use House #2 Simulation and Monthly Utility Bills, and Corresponding Three-parameter Change-point Regression Models for: (a) Electricity Use and (b) Natural Gas Use

5.2.1 Results of Calibration for Easy-to-use Case-study House #2 Simulation

The simulation of case-study house #2 was accomplished with the easy-to-use simulation and calibrated using the electricity and natural gas utility bills. Before starting the calibration, utility billing data was inspected to determine if an abnormal energy use data existed during the billing period. Figure 5.98 shows the utility billing data for: (a) electricity and (b) natural gas use against outdoor temperature and corresponding three-parameter change-point regression models. In addition, in a similar fashion as case-study house #1, the upper and lower dotted lines of 3P model lines, which represent the CV (RMSE) of the 3PC and 3PH model coefficients, were generated to identify the abnormal utility data. However, no modification of utility billing data performed for the case-study house #2 in this period because the outlier of the monthly energy use was not confirmed as an abnormal energy use by the homeowner.

The calibration of the easy-to-use case-study house #2 simulation was also carried out using the monthly utility billing data. CV (RMSE) changes for each parameter according to calibration procedure are shown in Appendix F. Figure 5.99 shows the calibrated energy use of the case-study house #2 simulation model against outdoor temperature, and Table 5.27 shows the final parameter values of the case-study house #2 calibrated simulation. In addition, Figure 5.100 shows the minimum global CV (RMSE) changes for each calibration procedure, and Figure 5.101 shows the total energy use changes for each calibration procedure. The final minimum global CV (RMSE) was 17.21% (14.23% for electricity use and 20.63% for natural gas use) for the case-study house #2, which was determined to be acceptable accuracy of calibration.



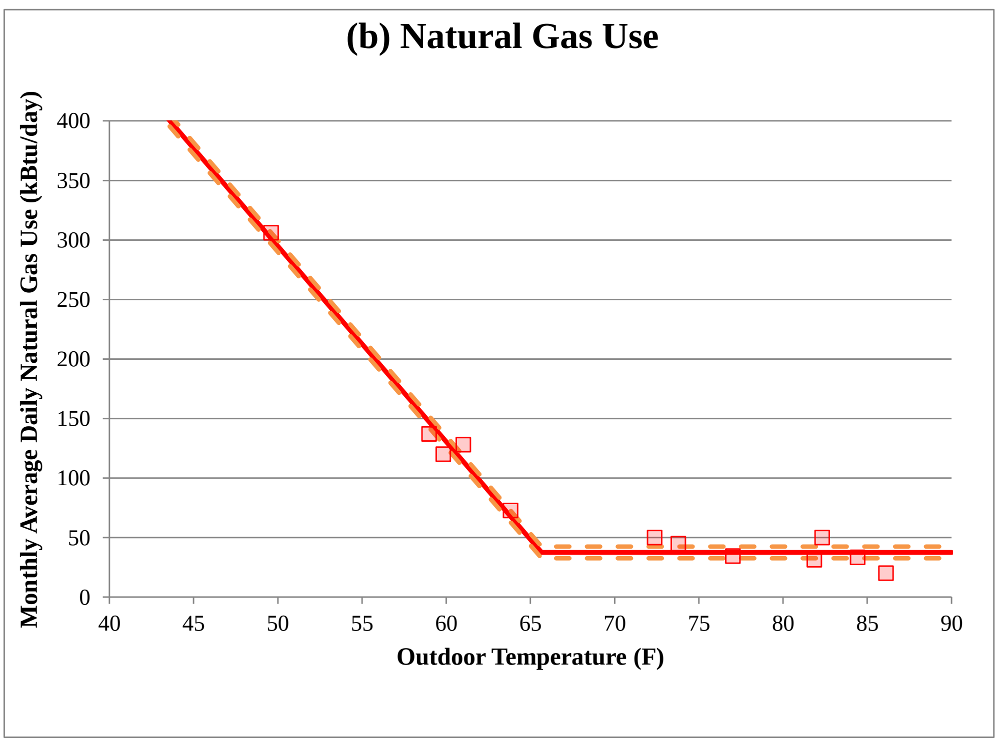
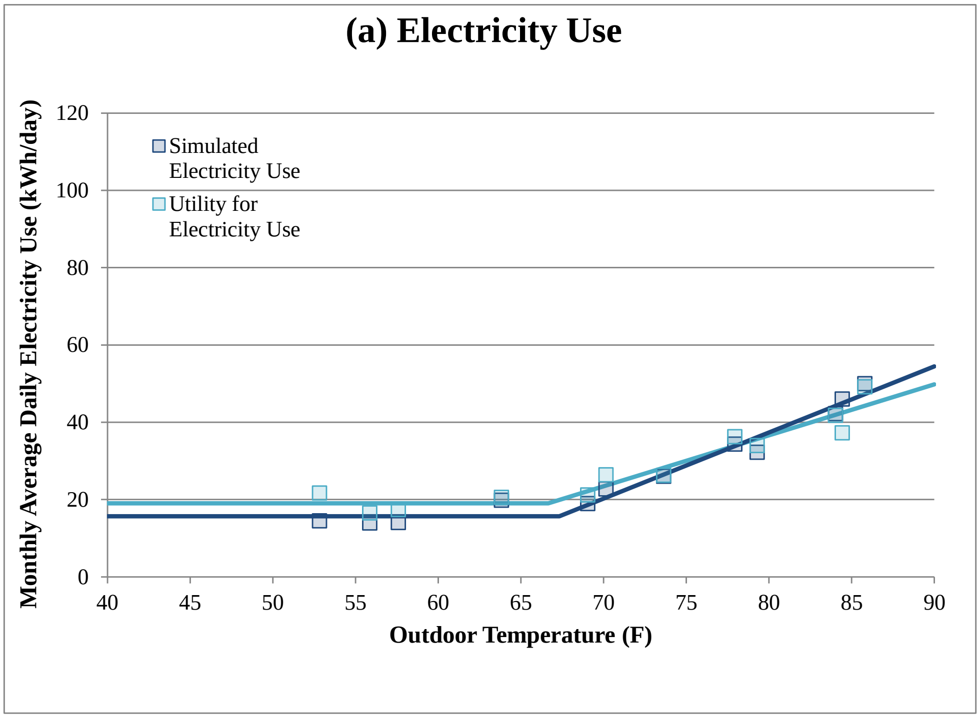


Figure 5.98 Monthly Utility Billing Data for: (a) Electricity and (b) natural Gas Use of House #2 with Upper and Lower Limitation Lines



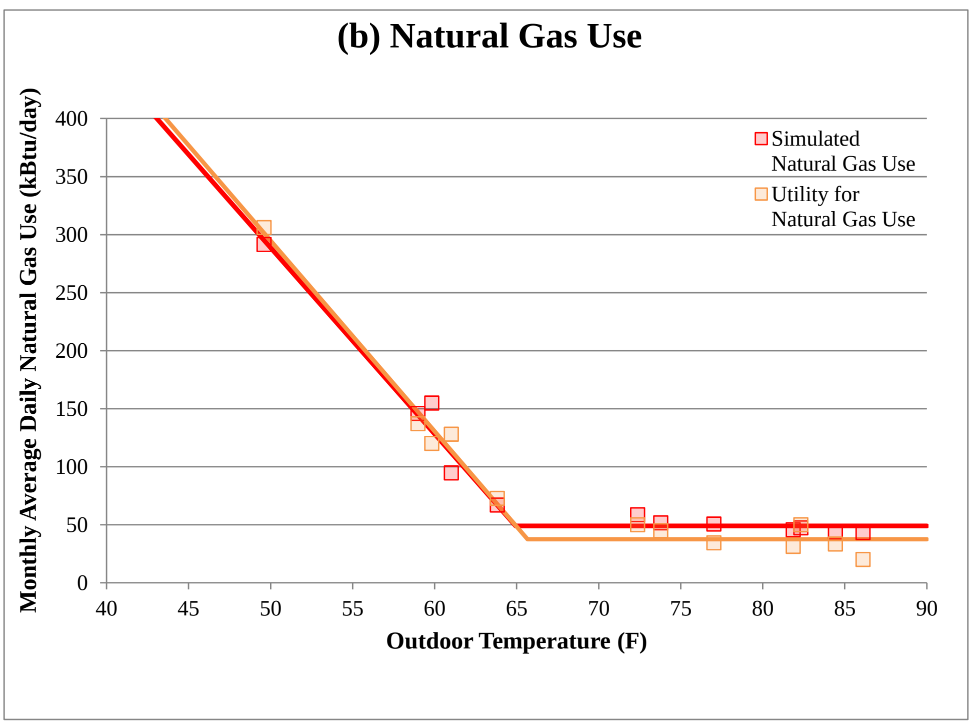


Figure 5.99 Results for the Calibrated Easy-to-use House #2 Simulation and Corresponding Three-parameter Change-point Regression Models for: (a) Electricity Use and (b) Natural Gas Use

Table 5.27 Each Parameter Value for the Easy-to-use House #2 after the Calibration Procedure

Calibration Run #	**3P Coefficient**		**Parameter**	**Easy-to-use Simulation**	
				Nominal	**Calibrated**
1	Baseload	Elec.	**L&E**	0.44	0.21
2		N.G.	**EF**	0.501	0.500
3	Change-point	Elec.	**Cooling Thermostat**	78	79.5
4		N.G.	**Heating Thermostat**	68	71.5
5	Slope	Elec.	**SEER**	11.07	13.5
6			**Return Duct Leakage**	0.100	0.090
7			**Roof Absorption**	0.75	0.88
8			**Supply Duct R-value**	8.0	6.4
9			**Supply Duct Leakage**	0.100	0.130
10			**Return Duct R-value**	4.0	11.1
11		N.G.	**AFUE**	0.83	0.79
12			**Window U-value**	0.7	0.62
13			**Infiltration Rate**	0.44	0.43
14			**Roof R-value**	24.26	21.80
15			**SHGC**	0.55	0.62
16			**Shading Devices**	0.0	1.2
17			**WWR North**	15	26.5
18			**WWR West**	15	4.5
19			**Wall R-value**	15.37	10.4
20			**Wall Absorption**	0.55	0.45
21			**WWR East**	15	33
22			**WWR South**	15	4.0
Elec. CV-RMSE				14.23%	
N.G. CV-RMSE				20.63%	
Global CV-RMSE				17.21%	

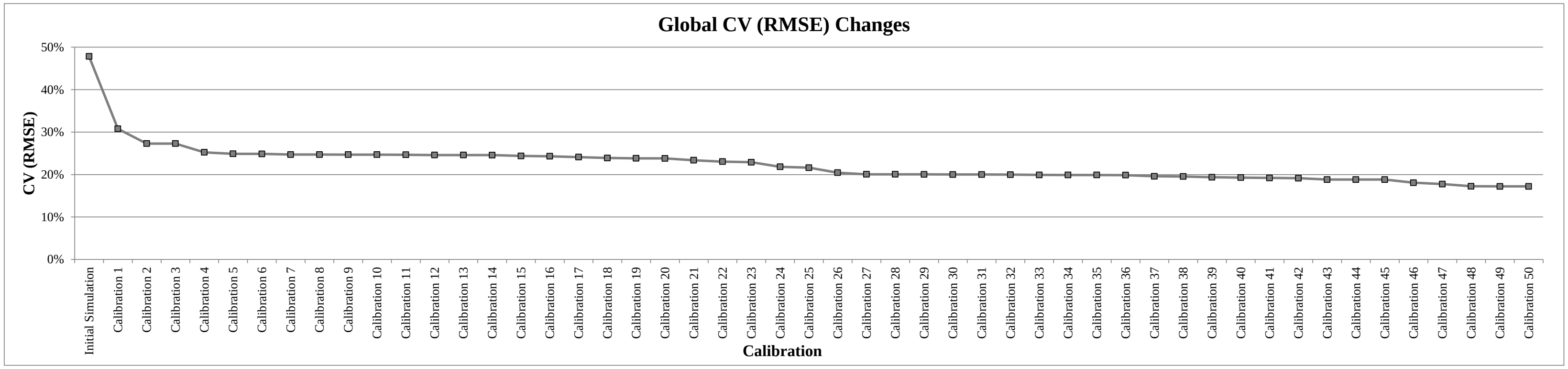


Figure 5.100 CV (RMSE) changes for the Easy-to-use House #2 by Each Calibration Procedure

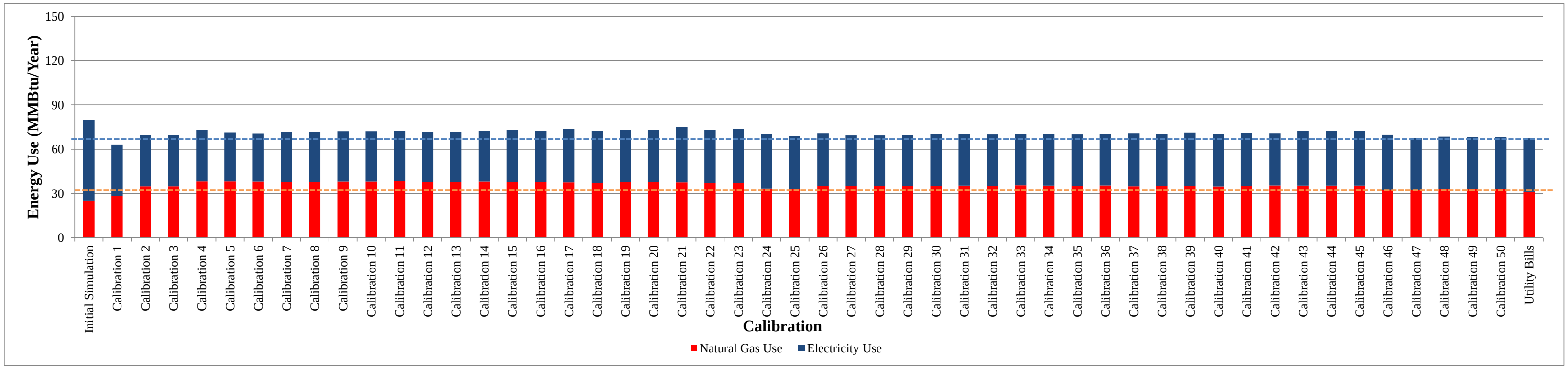


Figure 5.101 Energy Use Changes for Easy-to-use House #2 by Each Calibration Procedure

5.2.2 Determination of the Potential Energy Conservation Measures for Case-study House #2 using the Easy-to-use Simulation

The potential ECMs for the case-study house #2 were determined in a similar fashion to the potential ECMs for the case-study house#1.The annual energy savings and energy cost savings by the potential ECMs were then calculated to estimate a simple pay-back period for the most energy efficient and cost effective ECM(s).

For the determination of the potential ECMs, a standard house that is compliant with the 2009 IECC was modeled, and the parameter values were compared with the calibrated simulation parameters for the easy-to-use simulation. In this comparison, the candidates of the potential ECMs were decided as shown in 7th column of Table 5.28, which are the DHW EF, the return duct leakage, the supply duct R-value, the supply duct leakage, the infiltration rate, the roof R-value, the SHGC and the wall R-value.

For the next step, the annual energy savings of the case-study house #2 from each ECM was simulated and compared to the actual annual energy use of the house. Table 5.29 shows the ECM parameter values improvements of the energy efficient house. In order to find the most energy efficient and cost effective measures, the potential ECMs were grouped into four groups, which are: (1) for each ECM, (2) for a combination of envelope and fenestration ECMs, (3) for a combination of HVAC system ECMs and (4) for a combination of all ECMs. The four groups were then simulated.

Table 5.30 and Figure 5.102 show the annual energy savings, and Figure 5.31 and Figure 5.103 show the annual energy cost savings from the implementation of all the

Table 5.28 ECMs for the Case-study House #2 using the Easy-to-use Calibrated Simulation

3P Coefficient		Parameter	Calibrated Easy-to-use Simulation	A Standard House Simulation	% Difference	Improvement of Parameters	Potential ECM
Baseload	Elec.	L&E	0.21	0.58	176%		
	N.G.	EF	0.500	0.594	19%	**≥ 0.59**	**DHW**
Change-point	Elec.	Cooling Thermostat	79.5	75.0	6%		
	N.G.	Heating Thermostat	71.5	72.0	1%		
Slope	Elec.	SEER	13.50	13.00	4%		
		Return Duct Leakage	0.090	0.056	38%	**≤ 0.056**	**Duct**
		Roof Absorption	0.88	0.75	15%		
		Supply Duct R-value	6.4	8.0	25%	**≥ 8**	**Duct**
		Supply Duct Leakage	0.130	0.056	57%	**≤ 0.056**	**Duct**
		Return Duct R-value	11.1	6.0	46%		
	N.G.	AFUE	0.79	0.78	1%		
		Window U-value	0.62	0.65	5%		
		Infiltration Rate	0.43	0.35	19%	**≤ 0.35**	**Infiltration**
		Roof R-value	21.8	27.84	28%	**≥ 27.84**	**Roof Insulation**
		SHGC	0.62	0.30	52%	**≤ 0.3**	**Glazing**
		Shading Devices	1.2	0.0	100%		
		WWR North	26.5	20.8	22%		
		WWR West	4.5	20.8	362%		
		Wall R-value	10.4	11.8	13%	**≥ 11.8**	**Wall Insulation**
		Wall Absorption	0.45	0.75	67%		
		WWR East	33	20.8	37%		
		WWR South	4	20.8	420%		

ECMs. Negative total energy savings occurred for the supply duct R-value and the wall R-value because the annual energy use for the calibrated simulation was larger than actual annual energy use by 1.1%, which caused the negative energy savings in this case. This means that these ECMs were not energy efficient enough for the savings. Therefore, these ECMs were removed from the potential ECM list, and the new ECM list was simulated again. Table 5.32 and Figure 5.104 show the result of the new annual energy savings, and Table 5.33 and Figure 5.105 show the result of the new annual energy cost savings.

Next, the simple pay-back period for all ECMs was calculated based upon the cost information of unit and installation for all ECMs as shown in Table 5.34. The detail of the cost information for the unit and installation is shown in Appendix E. According to Table 5.34, the most energy efficient and cost effective ECMs were ECM 2 and 3 (i.e., combination of duct leakage measure) which had a 3.4 year pay-back period and ECM 9 (i.e., combination of EF and duct leakage measures) witch had a 9.9 year pay-back period.

Table 5.29 ECM Parameter Values for the Easy-to-use Case-study House #2 Simulation

3P Coefficient		Parameter	Improvement of Parameter Values	Potential ECM
Baseload	Elec.	L&E		
	N.G.	EF	**0.590**	**DHW**
Change-point	Elec.	Cooling Thermostat		
	N.G.	Heating Thermostat		
Slope	Elec.	SEER		
		Return Duct Leakage	**0.028**	**Duct**
		Roof Absorption		
		Supply Duct R-value	**8**	**Duct**
		Supply Duct Leakage	**0.028**	**Duct**
		Return Duct R-value		
	N.G.	AFUE		
		Window U-value		
		Infiltration Rate	**0.35**	**Infiltration**
		Roof R-value	**38**	**Roof Insulation**
		SHGC	**0.25**	**Glazing**
		Shading Devices		
		WWR North		
		WWR West		
		Wall R-value	**13**	**Wall Insulation**
		Wall Absorption		
		WWR East		
		WWR South		

Table 5.30 Annual Energy Savings from ECMs for House #2 using the Easy-to-use Calibrated Simulation

	ECM1	ECM2	ECM3	ECM4	ECM5	ECM6	ECM7	ECM8	ECM9	ECM10	ECM11	Utility
	EF (0.50 → 0.59)	Return Duct Leakage (0.090 → 0.028)	Supply Duct R-value (6.4 → 8.0)	Supply Duct Leakage (0.130 → 0.028)	Infiltration Rate (0.43 → 0.35)	Roof R-value (21.8 → 38.0)	SHGC (0.62 → 0.25)	Wall R-value (10.4 → 13.0)	Combination 1 (Envelope & Fenestration)	Combination 2 (HVAC Systems)	Combination 3 (All)	
Elec. Use (kWh)	10215	9447	10098	9637	10170	9638	8322	10177	7677	8832	6796	10624
Elec. Use (MMBtu)	34.9	32.2	34.5	32.9	34.7	32.9	28.4	34.7	26.2	30.1	23.2	36.3
N.G. Use (MMBtu)	30.2	32.5	33.1	32.0	32.5	30.7	38.3	32.7	35.1	27.5	29.1	31.1
Total Use (MMBtu)	65.1	64.7	67.5	64.9	67.2	63.6	66.7	67.4	61.3	57.7	52.2	67.4
Savings (MMBtu)	2.3	2.6	-0.2	2.4	0.1	3.7	0.7	-0.1	6.1	9.7	15.1	0.0
Total Savings (%)	3.5%	4.1%	-0.2%	3.8%	0.2%	5.9%	1.0%	-0.1%	9.9%	16.8%	28.9%	0.0%

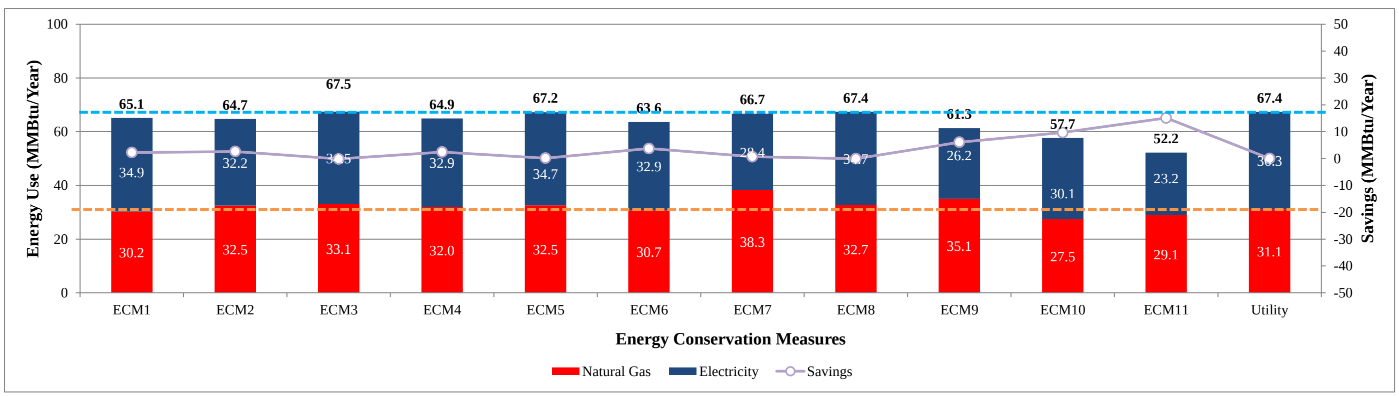


Figure 5.102 Annual Energy Savings from ECMs for House #2 using the Easy-to-use Calibrated Simulation

Table 5.31 Annual Energy Cost Savings from ECMs for House #2 using the Easy-to-use Calibrated Simulation

	ECM1	**ECM2**	**ECM3**	**ECM4**	**ECM5**	**ECM6**	**ECM7**	**ECM8**	**ECM9**	**ECM10**	**ECM11**	**Utility**
	EF (0.50 → 0.59)	Return Duct Leakage (0.090 → 0.028)	Supply Duct R-value (6.4 → 8.0)	Supply Duct Leakage (0.130 → 0.028)	Infiltration Rate (0.43 → 0.35)	Roof R-value (21.8 → 38.0)	SHGC (0.62 → 0.25)	Wall R-value (10.4 → 13.0)	Combination 1 (Envelope & Fenestration)	Combination 2 (HVAC Systems)	Combination 3 (All)	
Elec. Use ($/Year)	$ 1,141	$ 1,055	$ 1,128	$ 1,076	$ 1,136	$ 1,077	$ 930	$ 1,137	$ 858	$ 986	$ 759	$ 1,187
N.G. Use ($/Year)	$ 386	$ 415	$ 422	$ 409	$ 415	$ 392	$ 489	$ 417	$ 448	$ 351	$ 371	$ 397
Total Use ($/Year)	$ 1,527	$ 1,470	$ 1,550	$ 1,485	$ 1,551	$ 1,469	$ 1,419	$ 1,554	$ 1,305	$ 1,338	$ 1,130	$ 1,584
Savings ($/Year)	$ 57	$ 114	$ 34	$ 98	$ 32	$ 115	$ 165	$ 30	$ 278	$ 246	$ 454	$ -
Total Savings (%)	3.7%	7.7%	2.2%	6.6%	2.1%	7.8%	11.7%	1.9%	21.3%	18.4%	40.1%	0.0%

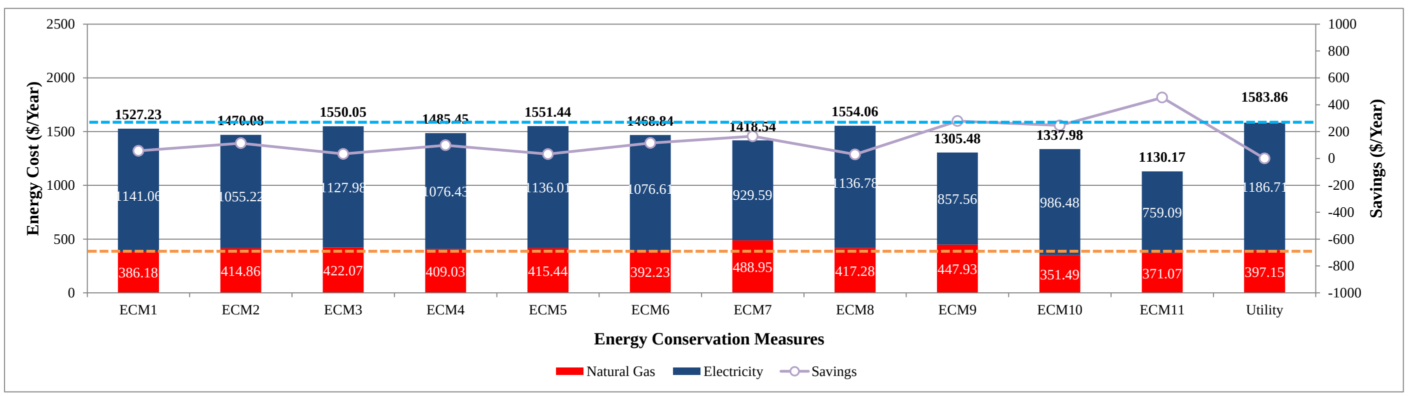


Figure 5.103 Annual Energy Cost Savings from ECMs for House #2 using the Easy-to-use Calibrated Simulation

Table 5.32 Annual Energy Savings from New ECMs for House #2 using the Easy-to-use Calibrated Simulation

	ECM1	ECM2	ECM3	ECM4	ECM5	ECM6	ECM7	ECM8	ECM9	Utility
	EF (0.50 → 0.59)	Return Duct Leakage (0.090 → 0.028)	Supply Duct Leakage (0.130 → 0.028)	Infiltration Rate (0.43 → 0.35)	Roof R-value (21.8 → 38.0)	SHGC (0.62 → 0.25)	Combination 1 (Envelope & Fenestration)	Combination 2 (HVAC Systems)	Combination 3 (All)	
Elec. Use (kWh)	10215	9447	9637	10170	9638	8322	7679	8946	6879	10624
Elec. Use (MMBtu)	34.9	32.2	32.9	34.7	32.9	28.4	26.2	30.5	23.5	36.3
N.G. Use (MMBtu)	30.2	32.5	32.0	32.5	30.7	38.3	34.9	28.3	29.7	31.1
Total Use (MMBtu)	65.1	64.7	64.9	67.2	63.6	66.7	61.1	58.8	53.2	67.4
Savings (MMBtu)	2.3	2.6	2.4	0.1	3.7	0.7	6.3	8.6	14.1	0.0
Total Savings (%)	3.5%	4.1%	3.8%	0.2%	5.9%	1.0%	10.3%	14.6%	26.6%	0.0%

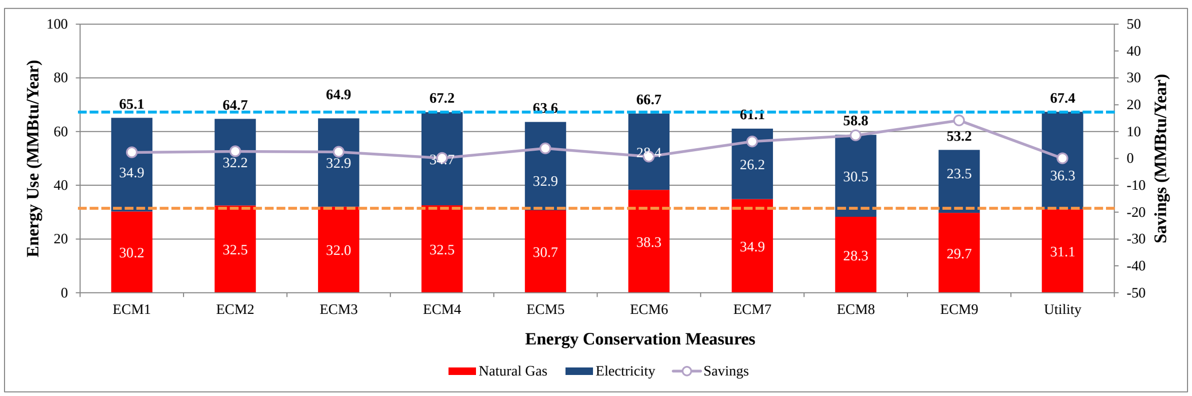


Figure 5.104 Annual Energy Savings from New ECMs for House #2 using the Easy-to-use Calibrated Simulation

Table 5.33 Annual Energy Cost Savings from New ECMs for House #2 using the Easy-to-use Calibrated Simulation

	ECM1	ECM2	ECM3	ECM4	ECM5	ECM6	ECM7	ECM8	ECM9	Utility
	EF (0.50 → 0.59)	Return Duct Leakage (0.090 → 0.028)	Supply Duct Leakage (0.130 → 0.028)	Infiltration Rate (0.43 → 0.35)	Roof R-value (21.8 → 38.0)	SHGC (0.62 → 0.25)	Combination 1 (Envelope & Fenestration)	Combination 2 (HVAC Systems)	Combination 3 (All)	
Elec. Use ($/Year)	$ 1,141	$ 1,055	$ 1,076	$ 1,136	$ 1,077	$ 930	$ 858	$ 999	$ 768	$ 1,187
N.G. Use ($/Year)	$ 386	$ 415	$ 409	$ 415	$ 392	$ 489	$ 445	$ 361	$ 380	$ 397
Total Use ($/Year)	$ 1,527	$ 1,470	$ 1,485	$ 1,551	$ 1,469	$ 1,419	$ 1,303	$ 1,360	$ 1,148	$ 1,584
Savings ($/Year)	$ 57	$ 114	$ 98	$ 32	$ 115	$ 165	$ 281	$ 224	$ 436	$ -
Total Savings (%)	3.7%	7.7%	6.6%	2.1%	7.8%	11.7%	21.6%	16.4%	38.0%	0.0%

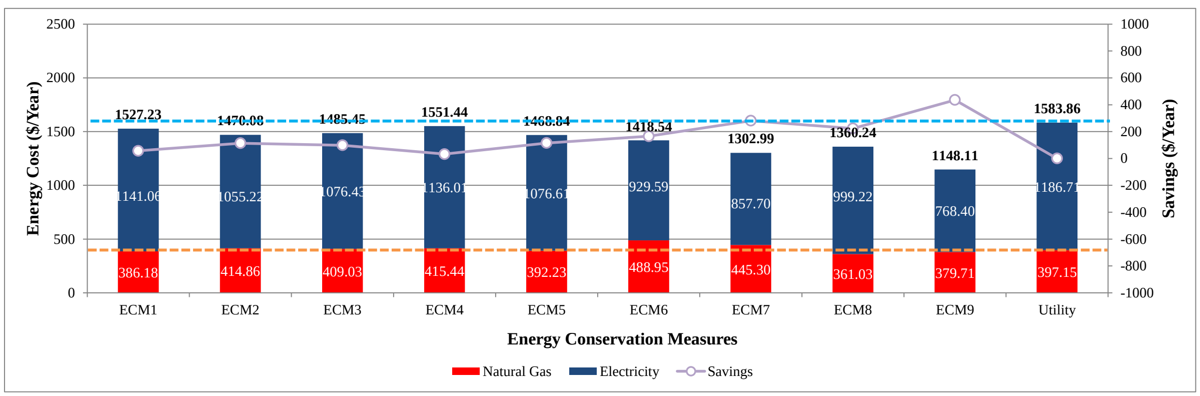


Figure 5.105 Annual Energy Cost Savings from New ECMs for House #2 using the Easy-to-use Calibrated Simulation

Table 5.34 Result of Simple Pay-back Period Calculation from New ECMs using the Easy-to-use House #2 Calibrated Simulation

Compenent Description		Unit	Unit Cost[1] [$]	Estimated Cost [$]	Annual Energy Savings [$]	Estimated Payback [yrs]
ECM 1						
Hot Water Heater[3] (50 gallon / 40000 Btu/hr)	EF 0.63	$/Unit	1,100	1,100	57	**19.3**
ECM 2&3						
Improved Duct Sealing[2]		$/ft^2	0.13	629	183	**3.4**
ECM 4						
Improved Envelope Sealing[2]		$/ft^2	0.2	484	32	**14.9**
ECM 5						
Fenestration	SHGC-0.25	$/ft^2	31.77	8,500	165	**51.4**
ECM 6						
Roof Blown-in Insulation	R-38	$/ft2	1.33	3,217	115	**28.0**
ECM 7						
Combination 1 (ECM 4, 5 and 6)				11,718	281	**41.7**
ECM 8						
Combination 2 (ECM 1, 2 and 3)				2,213	224	**9.9**
ECM 9						
Combination 3 (ECM 1, 2, 3, 4, 5 and 6)				13,930	436	**32.0**

Notes:
1. Costs inclusive of labor and equipment.
2. Incremental costs.
3. Assuming no charge for installation costs.

5.3 Description of Case-study House #3

Case-study house #3 is a single-family house located in Plano, Texas, which was built in 1994. The basic information about the building for the easy-to-use simulation (i.e., constructed year and location of the house) and photos were obtained from the homeowner. Figure 5.106 through Figure 5.109 shows the appearance of the case-study house taken from different points of view. The annual monthly utility bills for electricity use and natural gas use during 2011 and 2012 were also obtained from the homeowner to use as the measured energy use of the house for the calibration. Table 5.35and Table 5.36 show the monthly electricity and natural gas utility billing data, and calculated monthly average daily use, respectively.

In a similar fashion to the case-study house #1, the approval for this case-study house from the IRB for the research compliance and biosafety's human subject's protection program was also obtained and is attached in Figure A.1 in Appendix A.

The easy-to-use simulation was developed using the ESL's DDP software based on the building characteristic information shown in Table 4.3. The occupancy, lighting and equipment, and HVAC operating schedules were set to be run 24 hours per day for the whole year, and the building geometry was simplified for use with the DDP. The easy-to-use simulation was run with a TRY formatted weather file for Dallas, Texas (Figure D.4 in Appendix D), and hourly and average daily electricity and natural gas use were extracted from the hourly-report of the simulation output file. Figure 5.110 shows monthly average daily plots for the simulated and measured electricity and natural gas use against outdoor temperature, and Figure 5.111 shows the same energy use and their

3PC and 3PH regression models that were performed using the IMT. A monthly CV (RMSE) for the easy-to-use simulation was calculated as 77.2% for the electricity use, 74.4% for the natural gas use and 79.2% for global, respectively.

Figure 5.106 Front View (East) of the Case-study House #3

Figure 5.107 Back View (West) of the Case-study House #3

Figure 5.108   Side View (North) of the Case-study House #3

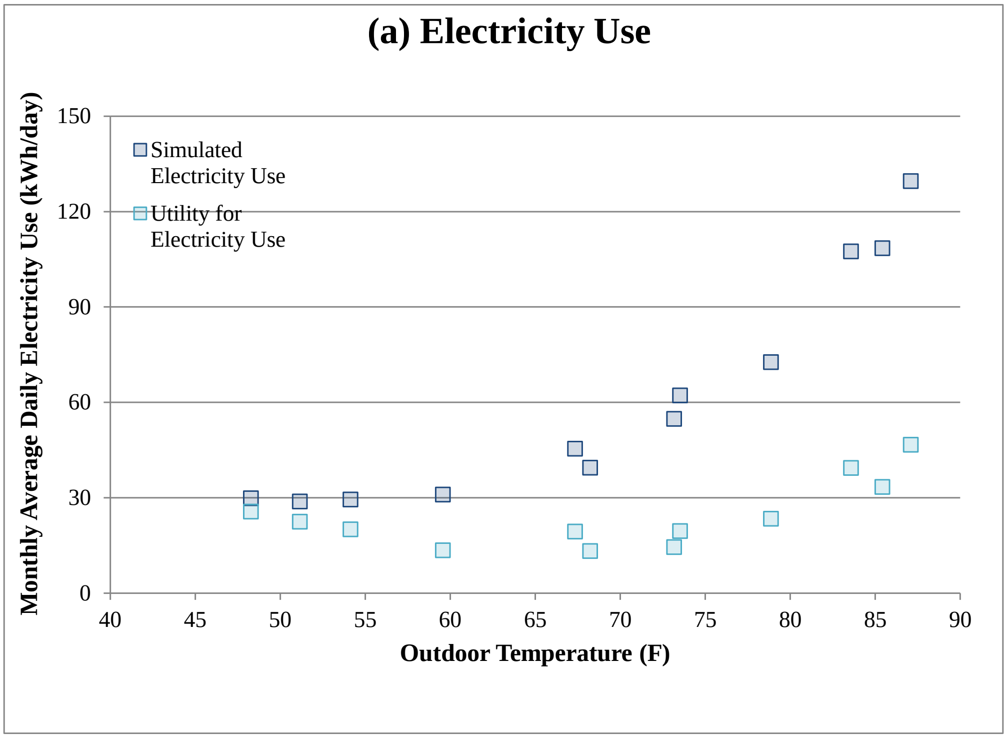
Figure 5.109   Side View (South) of the Case-study House #3

Table 5.35 Monthly Electricity Utility Billing Data for the Case-study House #3

Billing Period		Days in Billing Periods	Monthly Electricity Use (kWh)	Calculated Monthly Avg. Daily Elec. Use (kWh/Day)
Start Date	End Date			
12/9/2011	1/10/2012	33	846	25.6
1/11/2012	2/9/2012	30	672	22.4
2/10/2012	3/11/2012	31	621	20.0
3/12/2012	4/10/2012	30	396	13.2
4/11/2012	5/9/2012	29	418	14.4
5/10/2012	6/10/2012	32	747	23.3
6/11/2012	7/10/2012	30	1002	33.4
7/11/2012	8/8/2012	29	1352	46.6
8/9/2012	9/9/2012	32	1258	39.3
9/10/2012	10/8/2012	29	565	19.5
10/9/2012	11/6/2012	29	560	19.3
11/7/2012	12/9/2012	34	456	13.4

Table 5.36 Monthly Natural Gas Utility Billing Data for the Case-study #3

Billing Period		Days in Billing Periods	Monthly N.G. Use (MCF)	Monthly N.G. Use (MMBtu)	Calculated Monthly Avg. Daily N.G. Use (MMBtu/Day)
Start Date	End Date				
12/6/2011	1/5/2012	31	13.2	6.5	0.210
1/6/2012	2/5/2012	31	11.2	4.6	0.148
2/6/2012	3/4/2012	28	9	3.7	0.132
3/5/2012	4/4/2012	31	3	2.8	0.090
4/5/2012	5/2/2012	28	0.8	2	0.071
5/3/2012	6/3/2012	32	0.5	2.9	0.091
6/4/2012	7/4/2012	31	0.2	2.7	0.087
7/5/2012	8/5/2012	32	0.2	2.5	0.078
8/6/2012	9/4/2012	30	0.3	0.7	0.023
9/5/2012	10/4/2012	30	0.2	2.5	0.083
10/5/2012	11/2/2012	29	2.4	2.5	0.086
11/3/2012	12/5/2012	33	6	3.2	0.097



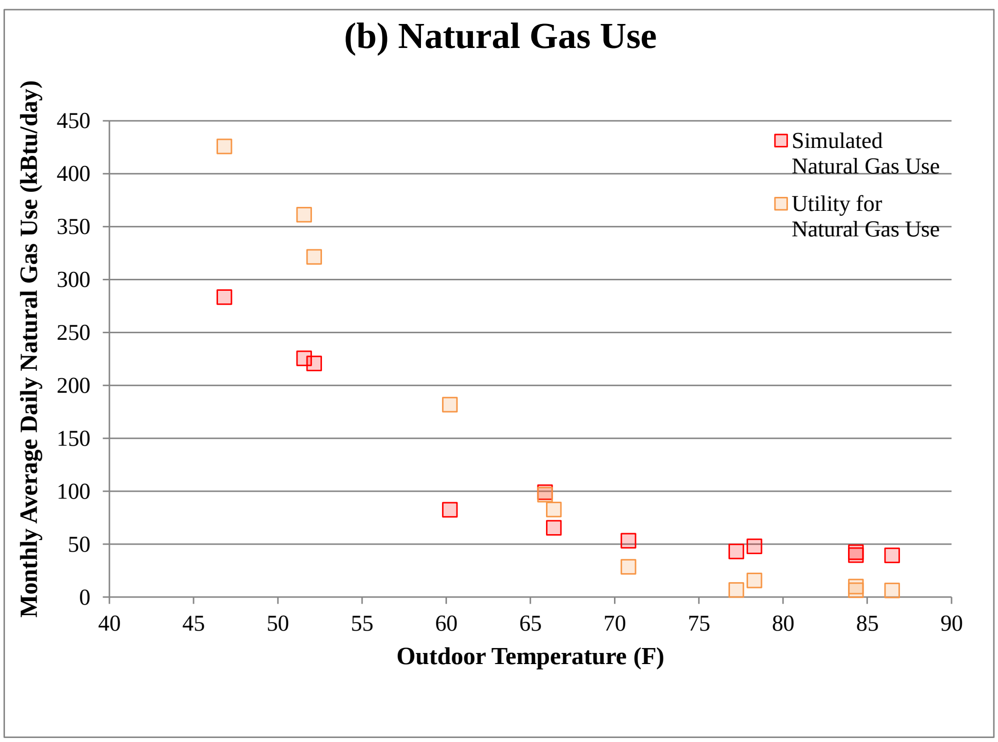
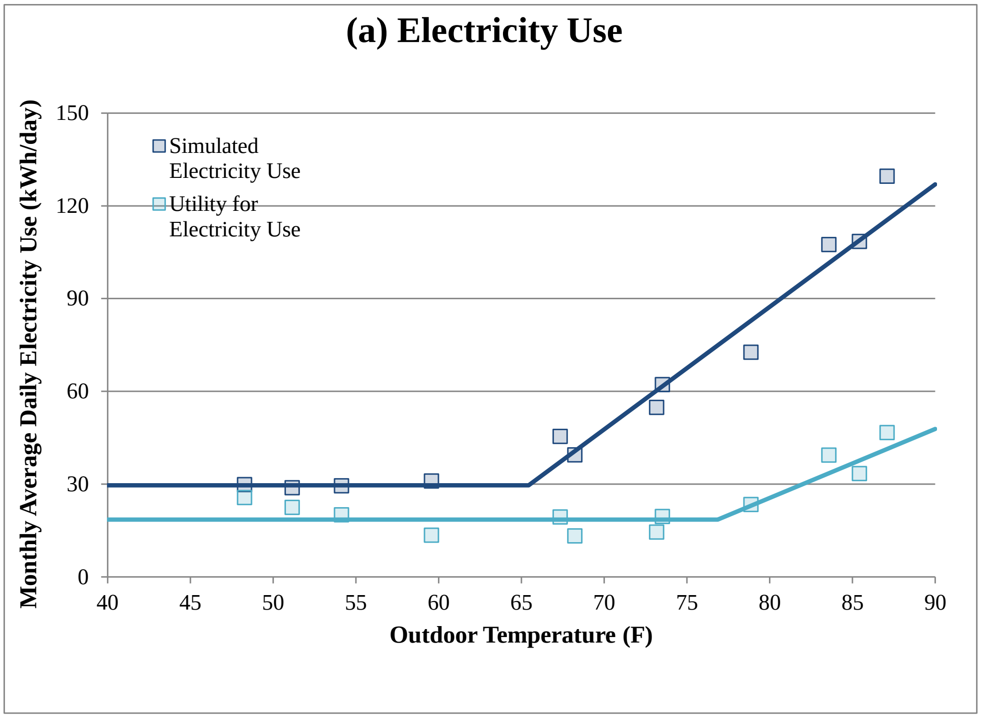


Figure 5.110 Results for the Easy-to-use House #3 Simulation and the Monthly Utility Bills for: (a) Electricity Use and (b) Natural Gas Use



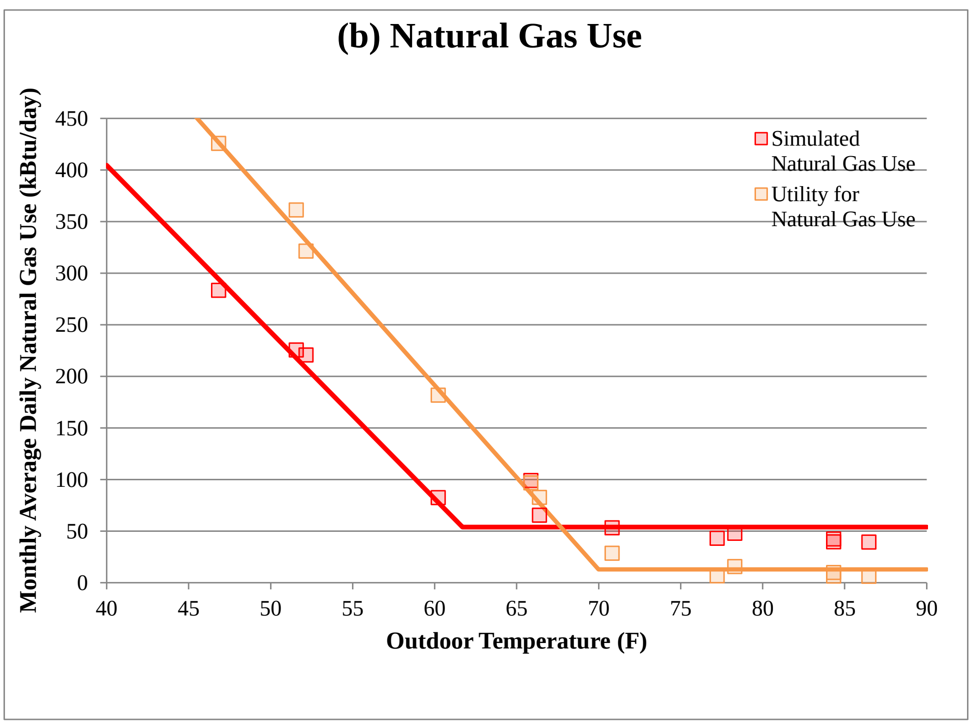


Figure 5.111 Results for the Easy-to-use House #3 Simulation and Monthly Utility Bills, and Corresponding Three-parameter Change-point Regression Models for: (a) Electricity Use and (b) Natural Gas Use

5.3.1 Results of Calibration for Easy-to-use Case-study House #3 Simulation

The simulation of case-study house #3 was accomplished with the easy-to-use simulation and calibrated using the electricity and natural gas utility bills. Before starting the calibration, utility billing data was inspected to determine if an abnormal energy use data existed during the billing period. Figure 5.112 shows the utility billing data for: (a) electricity and (b) natural gas use against outdoor temperature and corresponding three-parameter change-point regression models. In addition, in a similar fashion as case-study house #1, the upper and lower dotted lines of 3P model lines, which represent the CV (RMSE) of the 3PC and 3PH model coefficients, were generated to identify the abnormal utility data. However, no modification of utility billing data was performed for the case-study house #3 in this period because the outlier of the monthly energy use was not confirmed as an abnormal energy use by the homeowner.

The calibration of the easy-to-use case-study house #3 simulation was carried out using the monthly utility billing data. CV (RMSE) changes for each parameter according to calibration procedure are shown in Appendix G. Figure 5.113 shows the calibrated energy use of the case-study house #3 simulation model against outdoor temperature, and Table 5.37 shows the final parameter values of the case-study house #3 calibrated simulation. In addition, Figure 5.114 shows the minimum global CV (RMSE) changes for each calibration procedure, and Figure 5.115 shows total energy use changes for each calibration procedure. The final minimum global CV (RMSE) was 18.31% (12.25% for electricity use and 19.86% for natural gas use) for case-study house #3, which was an acceptable accuracy of calibration.

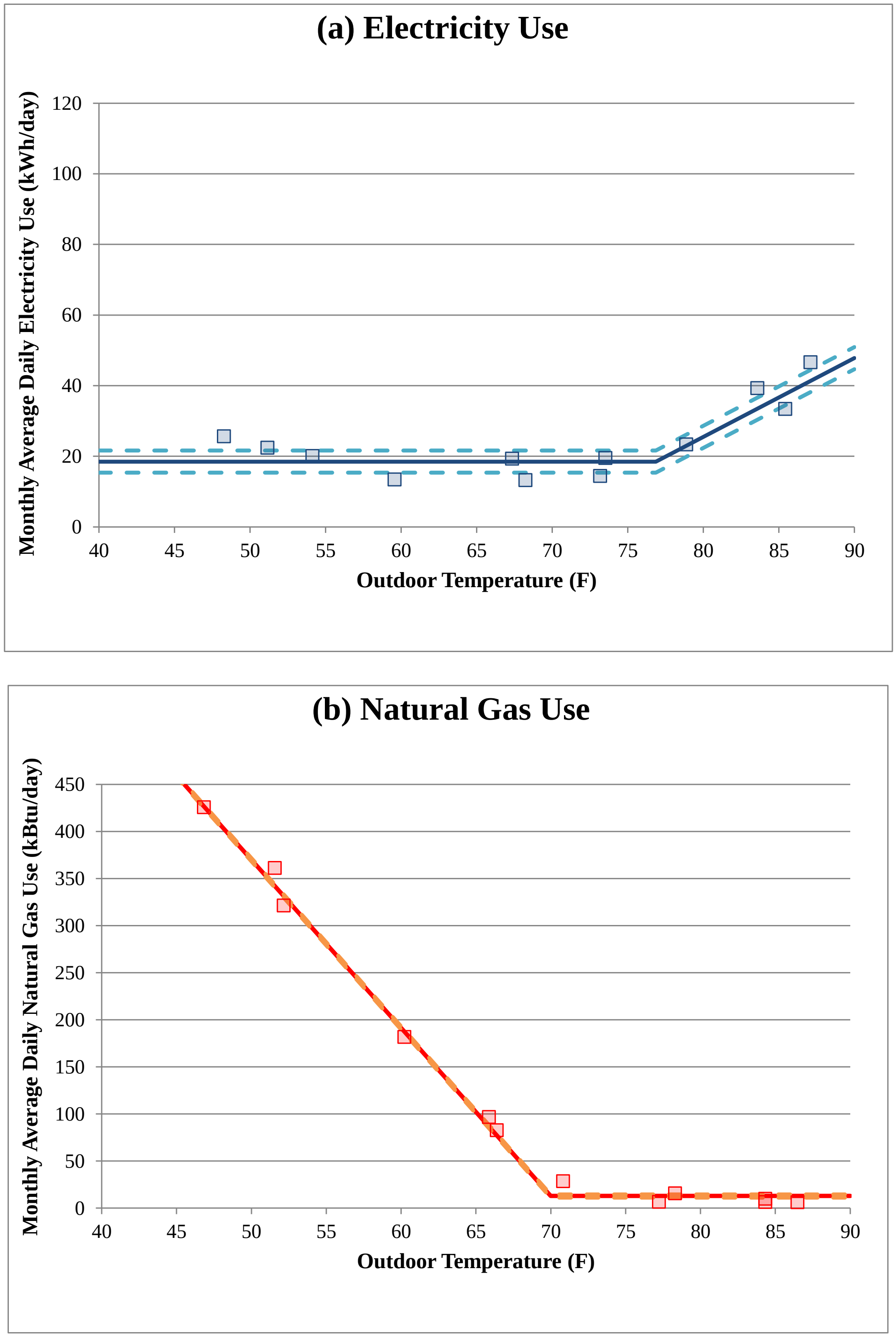
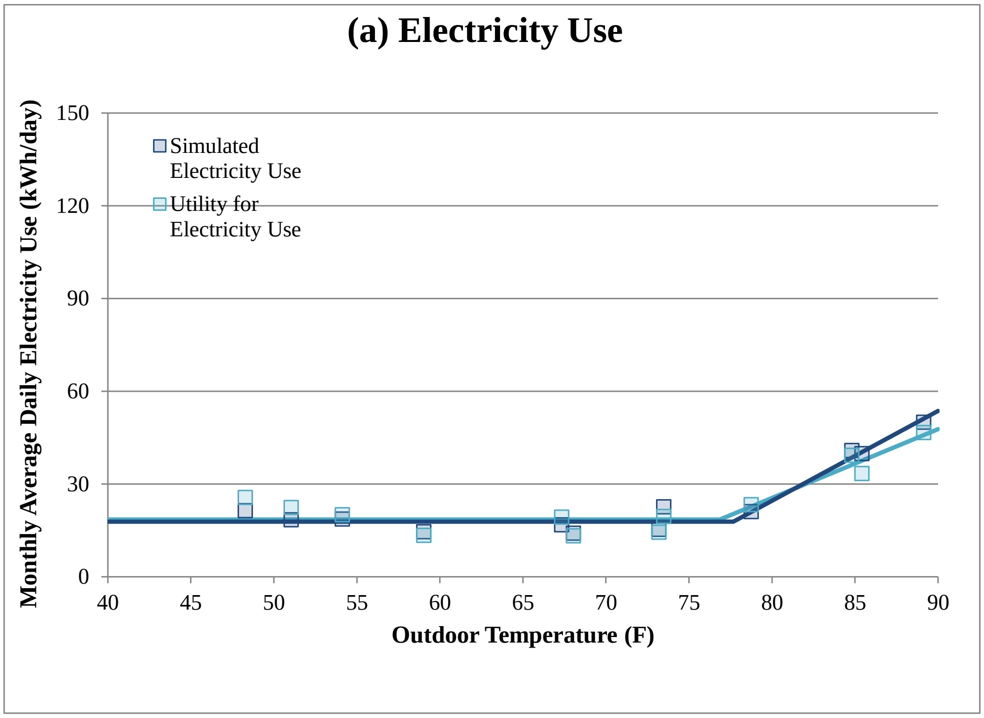


Figure 5.112 Monthly Utility Billing Data for: (a) Electricity and (b) natural Gas Use of House #3 with Upper and Lower Limitation Lines



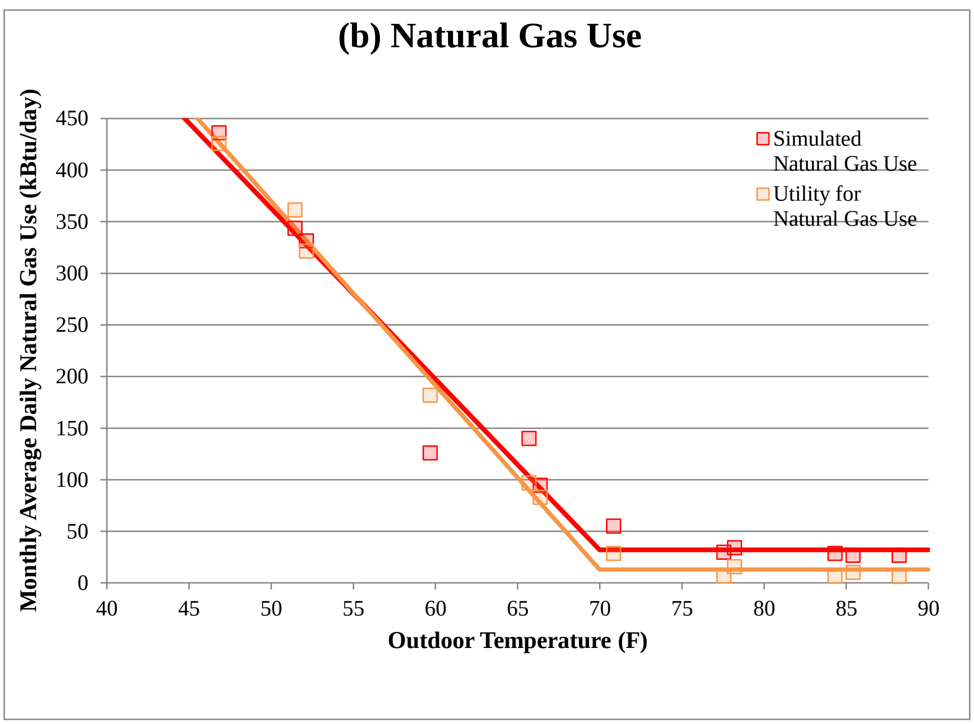


Figure 5.113 Results for the Calibrated Easy-to-use House #3 Simulation and Corresponding Three-parameter Change-point Regression Models for: (a) Electricity Use and (b) Natural Gas Use

Table 5.37 Each Parameter Value for Easy-to-use House #3 after the Calibration Procedure

Calibration Run #	3P Coefficient		Parameter	Easy-to-use Simulation	
				Nominal	Calibrated
1	Baseload	Elec.	**L&E**	0.44	0.13
2		N.G.	**EF**	0.501	0.710
3	Change-point	Elec.	**Cooling Thermostat**	78	87.5
4		N.G.	**Heating Thermostat**	68	72.5
5	Slope	Elec.	**SEER**	11.07	13.5
6			**Return Duct Leakage**	0.100	0.100
7			**Roof Absorption**	0.75	0.92
8			**Supply Duct R-value**	8.0	8.4
9			**Supply Duct Leakage**	0.100	0.110
10			**Return Duct R-value**	4.0	5.4
11		N.G.	**AFUE**	0.83	0.84
12			**Window U-value**	0.7	1.32
13			**Infiltration Rate**	0.44	0.42
14			**Roof R-value**	24.26	19.80
15			**SHGC**	0.55	0.86
16			**Shading Devices**	0.0	1.0
17			**WWR North**	15	22.5
18			**WWR West**	15	25
19			**Wall R-value**	15.37	13.4
20			**Wall Absorption**	0.55	0.12
21			**WWR East**	15	50
22			**WWR South**	15	9.5
Elec. CV-RMSE				12.25%	
N.G. CV-RMSE				19.86%	
Global CV-RMSE				18.31%	

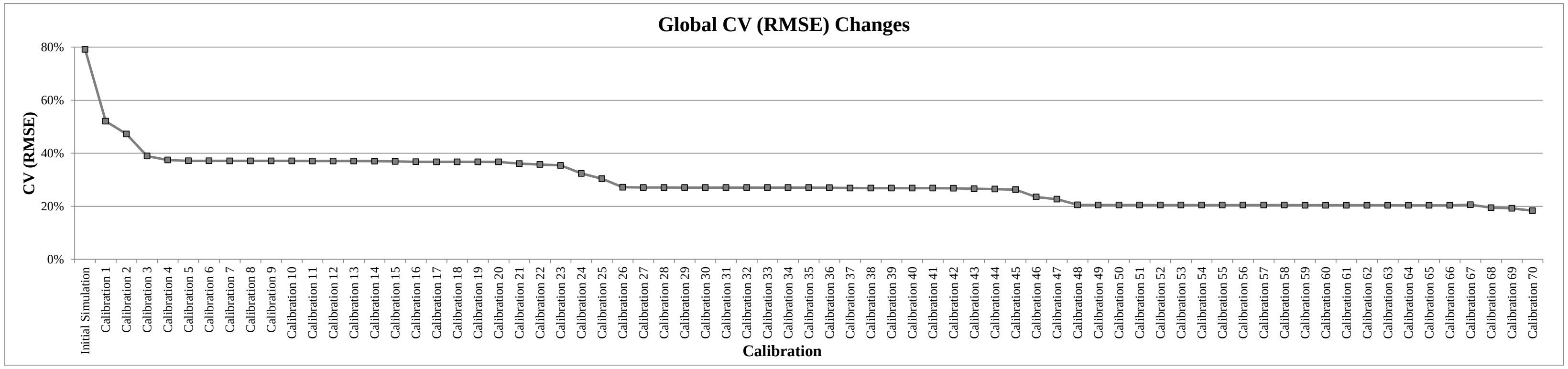


Figure 5.114 CV (RMSE) changes for the Easy-to-use House #3 by Each Calibration Procedure

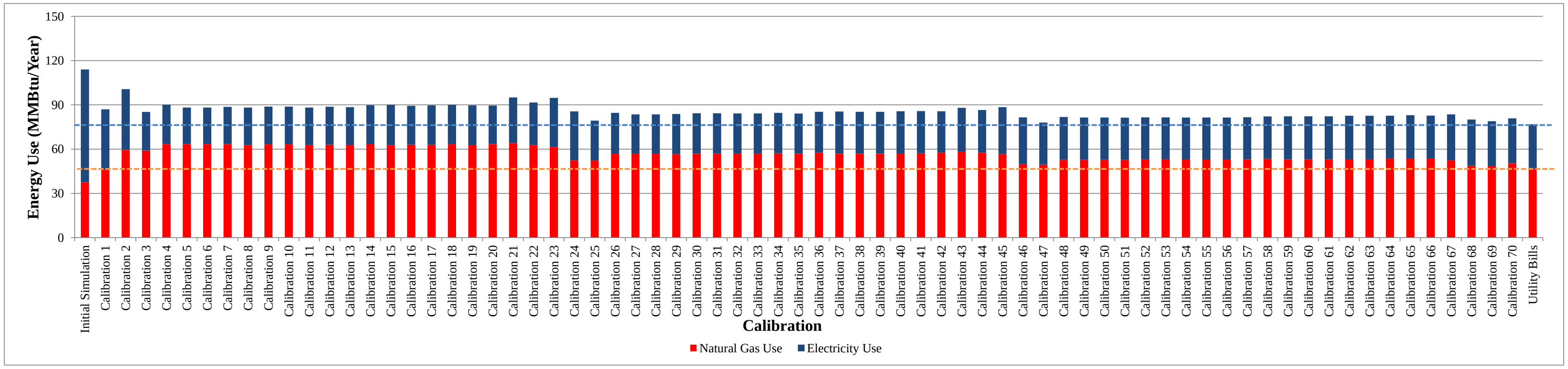


Figure 5.115 Energy Use Changes for Easy-to-use House #3 by Each Calibration Procedure

5.3.2 Determination of the Potential Energy Conservation Measures for Case-study House #3 using the Easy-to-use Simulation

As a similar fashion to the determination of the potential ECMs for the case-study house #1, the potential ECMs for the case-study house #3 were determined and the annual energy savings and energy cost savings by the potential ECMs were calculated to estimate a simple pay-back period for the most energy efficient and cost effective ECMs.

For the determination of the potential ECMs, a standard house, compliant with the 2009 IECC, was modeled and the parameter values were compared with the calibrated simulation parameters for the easy-to-use simulation. In this comparison, the candidates of the potential ECMs were decided as shown in 7th column of Table 5.38, which are the return duct leakage, the supply duct leakage, the window U-value, the infiltration rate, the roof R-value and the SHGC.

For the next step, the annual energy savings of the case-study house #3 from each ECM was simulated and compared to the actual annual energy use of the house. Table 5.39 shows the ECM parameter values for improvement of energy efficiency of the house. In order to find the most energy efficient and cost effective measures, the potential ECMs were grouped into four groups, which are: (1) for each ECM, (2) for a combination of envelope and fenestration ECMs, (3) for a combination of HVAC system ECMs and (4) for a combination of all ECMs, and simulated.

Table 5.38 ECMs for the Case-study House #3 using the Easy-to-use Calibrated Simulation

3P Coefficient		Parameter	Calibrated Easy-to-use Simulation	A Standard House Simulation	% Difference	Improvement of Parameters	Potential ECM
Baseload	Elec.	L&E	0.13	0.58	346%		
	N.G.	EF	0.710	0.594	16%		
Change-point	Elec.	Cooling Thermostat	87.5	75.0	14%		
	N.G.	Heating Thermostat	72.5	72.0	1%		
Slope	Elec.	SEER	13.50	13.00	4%		
		Return Duct Leakage	0.100	0.056	44%	**≤ 0.056**	**Duct**
		Roof Absorption	0.92	0.75	18%		
		Supply Duct R-value	8.4	8.0	5%		
		Supply Duct Leakage	0.110	0.056	49%	**≤ 0.056**	**Duct**
		Return Duct R-value	5.4	6.0	11%		
	N.G.	AFUE	0.84	0.78	7%		
		Window U-value	1.32	0.65	51%	**≤ 0.65**	**Glazing**
		Infiltration Rate	0.42	0.35	17%	**≤ 0.35**	**Infiltration**
		Roof R-value	19.8	27.84	41%	**≥ 27.84**	**Roof Insulation**
		SHGC	0.86	0.30	65%	**≤ 0.3**	**Glazing**
		Shading Devices	1.0	0.0	100%		
		WWR North	22.5	20.8	8%		
		WWR West	25.0	20.8	17%		
		Wall R-value	13.4	11.8	12%		
		Wall Absorption	0.12	0.75	525%		
		WWR East	50	20.8	58%		
		WWR South	9.5	20.8	119%		

Table 5.40 and Figure 5.116 show the annual energy savings, and Table 5.41 and Figure 5.117 show the annual energy cost savings from the implementation of all the ECMs. Negative total energy savings occurred for the supply and return duct leakage, the window U-value, the SHGC and the Roof R-value because the annual energy use for the calibrated simulation was larger than actual annual energy use by 4.9%, which caused the negative energy savings in this case. This means that these ECMs were not energy efficient enough for the savings. Therefore, these ECMs were removed from the

potential ECM list, and the new ECM list simulated. As a result, improving the building envelope sealing was the only ECM for the case-study house #3.

Next, the simple pay-back period for ECM was calculated based upon the cost information of unit and installation for the ECM as shown in Table 5.42. The detail of the cost information for the unit and installation is shown in Appendix E. The most cost effective ECM was ECM 3 (i.e., improve building envelope sealing) which had an 8.6 year pay-back period.

Table 5.39 ECM Parameter Values for the Easy-to-use Case-study House #3 Simulation

3P Coefficient		Parameter	Improvement of Parameter Values	Potential ECM
Baseload	Elec.	L&E		
	N.G.	EF		
Change-point	Elec.	Cooling Thermostat		
	N.G.	Heating Thermostat		
Slope	Elec.	SEER		
		Return Duct Leakage	**0.028**	**Duct**
		Roof Absorption		
		Supply Duct R-value		
		Supply Duct Leakage	**0.028**	**Duct**
		Return Duct R-value		
	N.G.	AFUE		
		Window U-value	**0.40**	**Glazing**
		Infiltration Rate	**0.35**	**Infiltration**
		Roof R-value	**38**	**Roof Insulation**
		SHGC	**0.25**	**Glazing**
		Shading Devices		
		WWR North		
		WWR West		
		Wall R-value		
		Wall Absorption		
		WWR East		
		WWR South		

Table 5.40 Annual Energy Savings from ECMs for House #3 using the Easy-to-use Calibrated Simulation

	ECM1	ECM2	ECM3	ECM4	ECM5	ECM6	ECM7	ECM8	ECM9	Utility
	Return Duct Leakage (0.100 → 0.028)	Supply Duct Leakage (0.110 → 0.028)	Infiltration Rate (0.42 → 0.35)	Window U-value (1.32 → 0.40)	SHGC (0.86 → 0.25)	Roof R-value (19.8 → 38.0)	Combination 1 (Envelope & Fenestration)	Combination 2 (HVAC Systems)	Combination 3 (All)	
Elec. Use (kWh)	9881	9935	10622	10503	9973	7755	5880	9279	5305	8738
Elec. Use (MMBtu)	33.7	33.9	36.2	35.8	34.0	26.5	20.1	31.7	18.1	29.8
N.G. Use (MMBtu)	45.4	44.8	26.2	46.5	43.9	64.2	33.4	42.8	30.6	46.7
Total Use (MMBtu)	79.1	78.7	62.5	82.3	78.0	90.6	53.5	74.4	48.7	76.5
Savings (MMBtu)	-2.6	-2.3	14.0	-5.8	-1.5	-14.1	23.0	2.1	27.8	0.0
Total Savings (%)	-3.3%	-2.9%	22.4%	-7.1%	-1.9%	-15.6%	43.0%	2.8%	57.1%	0.0%

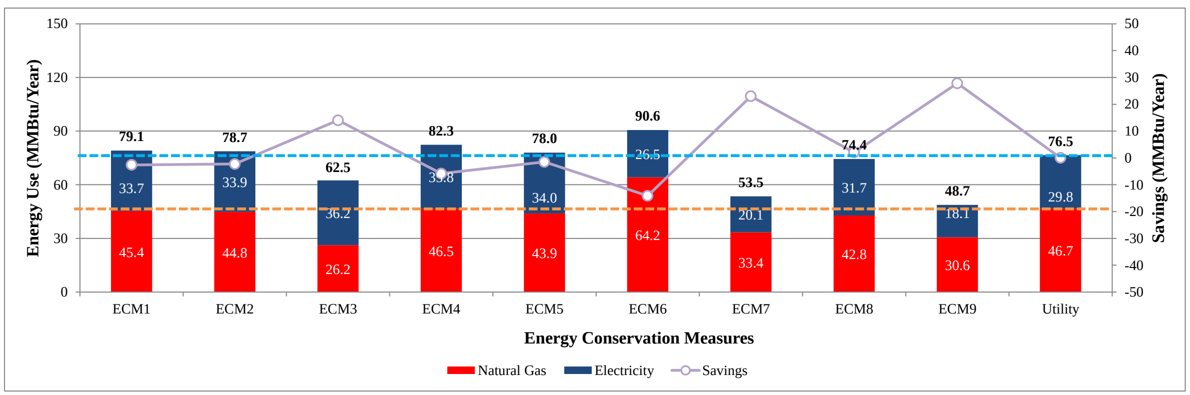


Figure 5.116 Annual Energy Savings from ECMs for House #3 using the Easy-to-use Calibrated Simulation

Table 5.41 Annual Energy Cost Savings from ECMs for House #3 using the Easy-to-use Calibrated Simulation

	ECM1	ECM2	ECM3	ECM4	ECM5	ECM6	ECM7	ECM8	ECM9	Utility
	Return Duct Leakage (0.100 → 0.028)	Supply Duct Leakage (0.110 → 0.028)	Infiltration Rate (0.42 → 0.35)	Window U-value (1.32 → 0.40)	SHGC (0.86 → 0.25)	Roof R-value (19.8 → 38.0)	Combination 1 (Envelope & Fenestration)	Combination 2 (HVAC Systems)	Combination 3 (All)	
Elec. Use ($/Year)	$ 1,104	$ 1,110	$ 1,187	$ 1,173	$ 1,114	$ 866	$ 657	$ 1,036	$ 593	$ 976
N.G. Use ($/Year)	$ 580	$ 573	$ 335	$ 594	$ 561	$ 819	$ 427	$ 546	$ 391	$ 596
Total Use ($/Year)	$ 1,683	$ 1,682	$ 1,522	$ 1,767	$ 1,675	$ 1,686	$ 1,084	$ 1,583	$ 983	$ 1,572
Savings ($/Year)	$ (111)	$ (110)	$ 51	$ (195)	$ (103)	$ (113)	$ 488	$ (11)	$ 589	$ -
Total Savings (%)	-6.6%	-6.6%	3.3%	-11.0%	-6.2%	-6.7%	45.0%	-0.7%	59.9%	0.0%

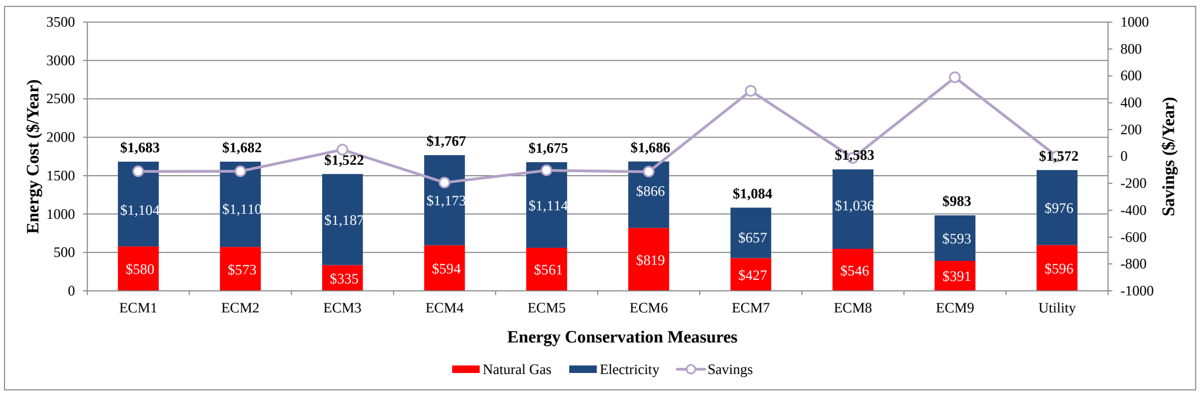


Figure 5.117 Annual Energy Cost Savings from ECMs for House #3 using the Easy-to-use Calibrated Simulation

Table 5.42 Result of Simple Pay-back Period Calculation from New ECMs for House #3 using the Easy-to-use Calibrated Simulation

Compenent Description	Unit	Unit Cost[1] [$]	Estimated Cost [$]	Annual Energy Savings [$]	Estimated Payback [yrs]
ECM 3					
Improved Envelope Sealing[1]	$\$/ft^2$	0.20	434	50.58	8.6

Notes:

1. Incremental costs.

5.4 Summary of Results

This chapter presents the results of the easy-to-use simulations, calibrated simulations and the resultant determination of the potential energy conservation measures (ECMs) for three case-study houses, along with the results of the sensitivity analysis which was used for the calibration procedure. In addition, the results of the calibration and the determination of the potential ECM using the easy-to-use simulation was predicted and compared with those using the as-built simulation.

5.4.1 Summary of Results for Case-study House #1

Case-study house #1 was a single-family house located in College Station, Texas. It was simulated using the as-built house information, the easy-to-use house information, and calibrated using the methodology developed in this study. After the calibration, the result of the easy-to-use calibrated simulation was compared with the results from the as-built calibrated simulation to verify the accuracy of using the easy-to-use simulation. The comparison result shows that the global CV (RMSE) for the as-built and the easy-to-use calibrated simulations were 8.8% and 9.1%, respectively, which was a 0.3% of difference between the two models. The CV (RMSE) for electricity and natural gas were also calculated as 6.8% and 7.6% for electricity, and 12.7% and 12.4% for natural gas use for the as-built calibrated simulation and the easy-to-use calibrated simulation respectively, which are differences of less than 1% between both models.

In addition, the resultant parameters for the as-built calibrated simulation and the easy-to-use calibrated simulation were compared. From the comparison, it was found that the most influential parameters for the calibrated simulation for the case-study house

#1 were the Lighting and Equipment (L&E) and the Energy Factor (EF). The final values for these parameters were close to each other with differences of 7.3% for the L&E and 9.7% for the EF. Some of the other parameters had approximately a 10% differences between the models. However, the differences for the global CV (RMSE) between two models were within 1.0%, so the other parameters were determined to be less significant parameters for the calibrations. The comparison of calibrated as-built simulation parameters with the easy-to-use simulation showed that the easy-to-use simulation yielded similar results as the as-built simulation using the calibration methodology developed in this thesis.

In the next step, the potential energy conservation measures for the case-study house #1 were determined. In this step, in a similar fashion to the step for the calibration, the as-built calibrated simulation and the easy-to-use calibrated simulation were both evaluated. To begin, the calibrated parameters for both simulations were compared with the parameters from the standard house that is compliant with the 2009 IECC. In this comparison, the parameters that were less energy efficient than the standard house were selected as potential energy conservation measures for the case-study house #1. Each measure and combination of measures were then simulated and compared with the current utility energy use to calculate savings. In addition, a simple pay-back calculation was performed to find the most energy efficient and cost effective measures, which have a pay-back period that is less than 10 years. Using this procedure, the most energy efficient and cost effective potential ECMs from the as-built and easy-to-use simulations were determined to be an improved EF; an improved duct leakage; a combination of an improved EF and improved supply/return duct leakage; and a combination of improved EF, improved SEER and improved duct leakage. The EF measure had 4.9 year of pay-back as determined by the as-built calibrated simulation, as well as a 4.9 year of pay-back from the easy-to-use calibrated simulation; The duct leakage measure had a 3.4 year of pay-back as determined by the as-built calibrated simulation, and had a 2.1 year pay-back from the easy-to-use calibrated simulation; The combination of EF and duct leakage measure had a 4.0 year of pay-back as determined by the as-built calibrated simulation, and had a 3.8 year of pay-back from the easy-to-use calibrated simulation; The combination of EF, SEER and duct leakage measure had a 7.7 year of pay-back as determined by the as-built calibrated simulation, and had a 7.1 year of pay-back from the easy-to-use calibrated simulation.

5.4.2 Summary of Results for Case-study House #2

Case-study house #2 was also a single-family house located in College Station, Texas. It was simulated using the easy-to-use house information, and calibrated using the methodology developed in this study. For the measured energy use data, one year of monthly utility billing data for electricity and natural gas were used. As a result of the calibration, the global CV (RMSE) of 47.8% with 40.7% CV (RMSE) for the electricity and 64.9% CV (RMSE) for the natural gas were improved to a global CV (RMSE) of 17.2% with 14.2% CV (RMSE) for the electricity and 20.6% CV (RMSE) for the natural gas.

After the calibration, potential energy conservation measures for the case-study house #2 were determined. In this step, the calibrated parameters for the easy-to-use simulations were compared with the parameters that were modeled using a standard house that is compliant with the 2009 IECC. The calibrated parameters that were less energy efficient than the parameters for the standard house were selected as candidates for the potential measures for the case-study house #2. Some of the candidates for the measures were dropped from the ECM list since they were not energy efficient enough. The final potential measures for the case-study house #2 were an improved EF for the DHW, an improved return duct leakage and supply duct leakage, an improved infiltration rate, roof R-value and SHGC. Each measure and combination of measures (combination of measures for building envelope and fenestration, HVAC systems and all of measures) were simulated to identify energy savings and energy cost savings. Finally, a simply-payback period was calculated for the selected potential measures. The improved supply & return duct sealing, and the combination of improved EF and improved duct sealing for the case-study house #2 were selected as the most energy efficient and cost effective measures, which had a 3.4 year pay-back period and a 9.9 year pay-back period, respectively.

5.4.3 Summary of Results for Case-study House #3

Case-study house #3 is a single-family house located in Plano, Texas. It was simulated using the easy-to-use house information, and calibrated using the methodology developed in this study. For measured energy use data, one year of monthly utility billing data for electricity and natural gas was used. As a result of the calibration, the 79.2% global CV (RMSE), 77.2% CV (RMSE) for the electricity and 74.4% CV

(RMSE) for the natural gas were improved to be an 18.3% global CV (RMSE), a 12.3% CV (RMSE) for the electricity and a 19.9% CV (RMSE) for the natural gas.

After the calibration, the potential energy conservation measures for the case-study house #3 were determined. In this step, the calibrated parameters for the easy-to-use simulations were compared with the parameters from a standard house that is compliant with the 2009 IECC. The calibrated parameters that were less energy efficient than the parameters for the standard house were selected as candidates for the potential measures for the case-study house #3. Some of the candidates for the measures were dropped from the list since they were not energy efficient enough. The final potential measure for the case-study house #3 was an improved infiltration rate, and the measure was simulated to estimate energy savings and energy cost savings.

Next, the simple pay-back calculation for the selected potential measure, which was improving the envelope sealing, was performed for the case-study house #3. This measure was then selected as the most energy efficient and cost effective measure along with an 8.6 year pay-back period.

5.4.4. Summary of Results for Case-study House #1, #2 and #3

The single-family houses #1 and #2 (located in College Station, Texas) and house #3 (located in Plano, Texas) were simulated using the easy-to-use simulation and calibrated using the methodology developed in this study. After that, the most energy efficient and cost effective energy conservation measures for three houses were determined. Figure 5.118 through Figure 5.121, Figure 5.122 through Figure 5.123, and Figure 5.124 show summary of the energy savings and energy cost savings for the house

#1, #2 and #3, respectively, using the most energy efficient and cost effective measures which were determined by the simple pay-back period calculations. Annual energy savings and energy cost savings for the case-study house #1 by improving EF was 17 MMBtu/year and 222 $/year respectively; by improving duct sealing was 3.5 MMBtu/year and 261 $/year respectively; by improving EF and duct sealing were 24 MMBtu/year and 458 $/year respectively; and by improving EF, SEER and duct sealing were 31 MMBtu/year and 672 $/year. Those for the case-study house #2 by improving duct sealing were 5 MMBtu/year and 183 $/year respectively, and by improving EF and duct sealing were 9 MMBtu/year and 224 $/year respectively. Those for case-study house #3 by improving envelope sealing were 14 MMBtu/year and 51 $/year respectively.

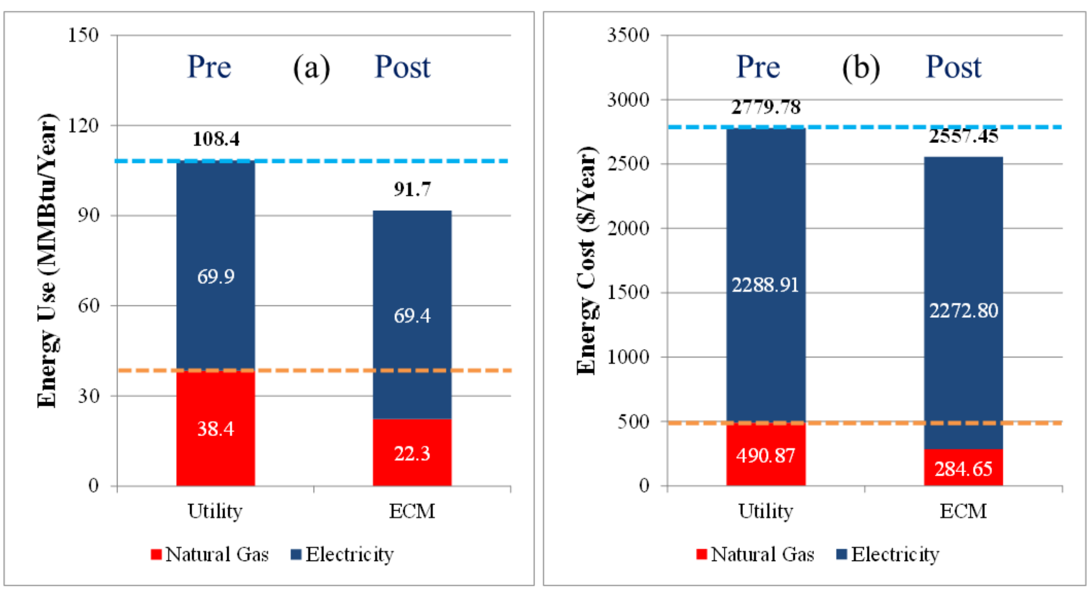


Figure 5.118 (a) Annual Energy Savings and (b) Energy Cost Savings by the Selected ECM for the Case-study House #1 (4.9 Year of Pay-back ECM: Improving EF from 0.31 to 0.59)

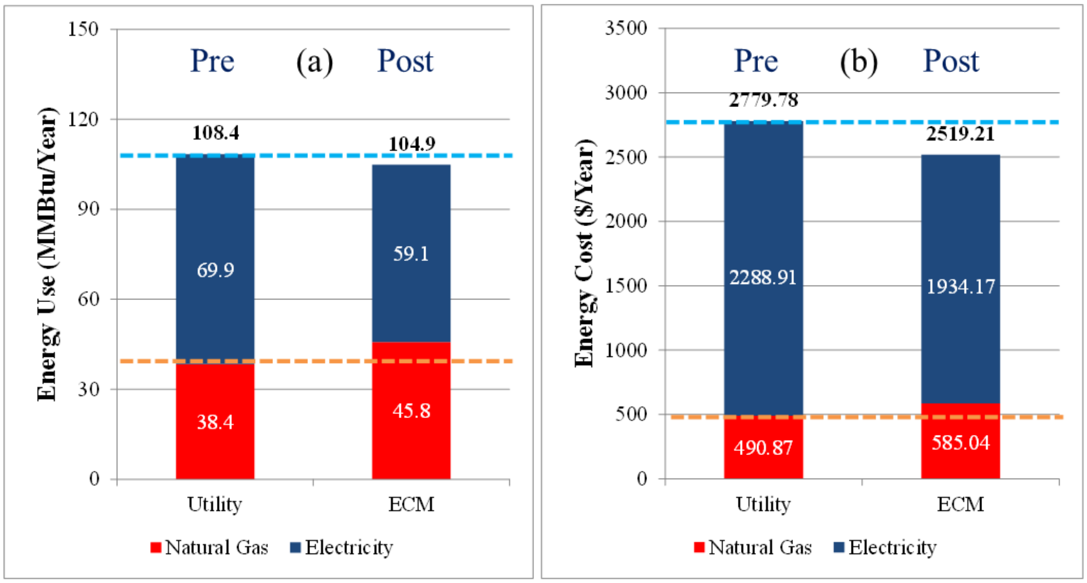


Figure 5.119 (a) Annual Energy Savings and (b) Energy Cost Savings by the Selected ECM for the Case-study House #1 (2.1 Year of Pay-back ECM: Improving Duct Sealing from 0.1 to 0.028)

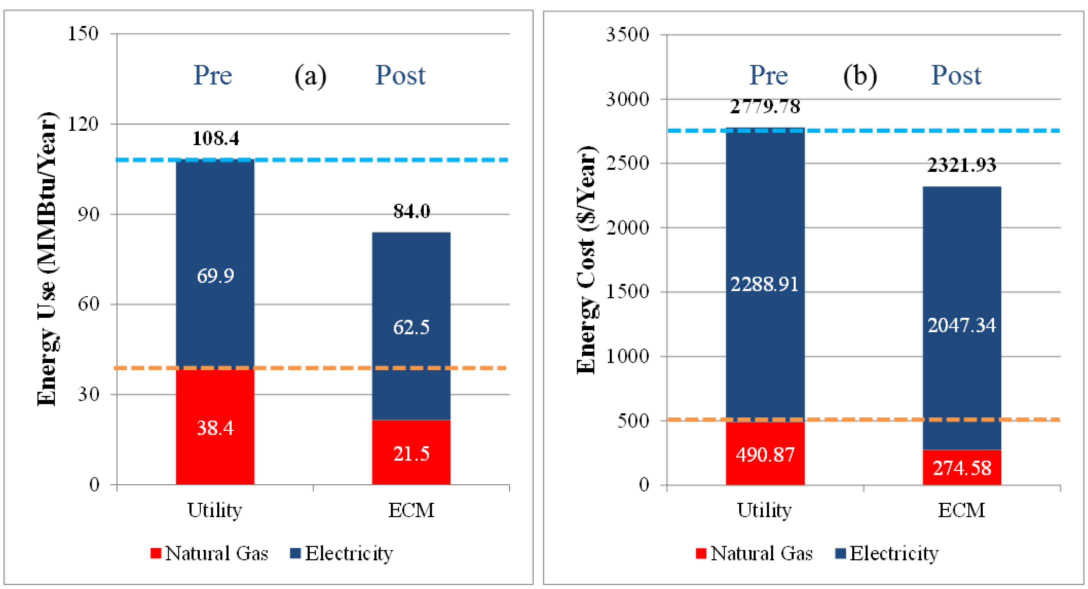


Figure 5.120 (a) Annual Energy Savings and (b) Energy Cost Savings by the Selected ECMs for the Case-study House #1 (3.8 Year of Pay-back ECM: Improving EF from 0.31 to 0.59; Improving Duct Sealing from 0.1 to 0.028)

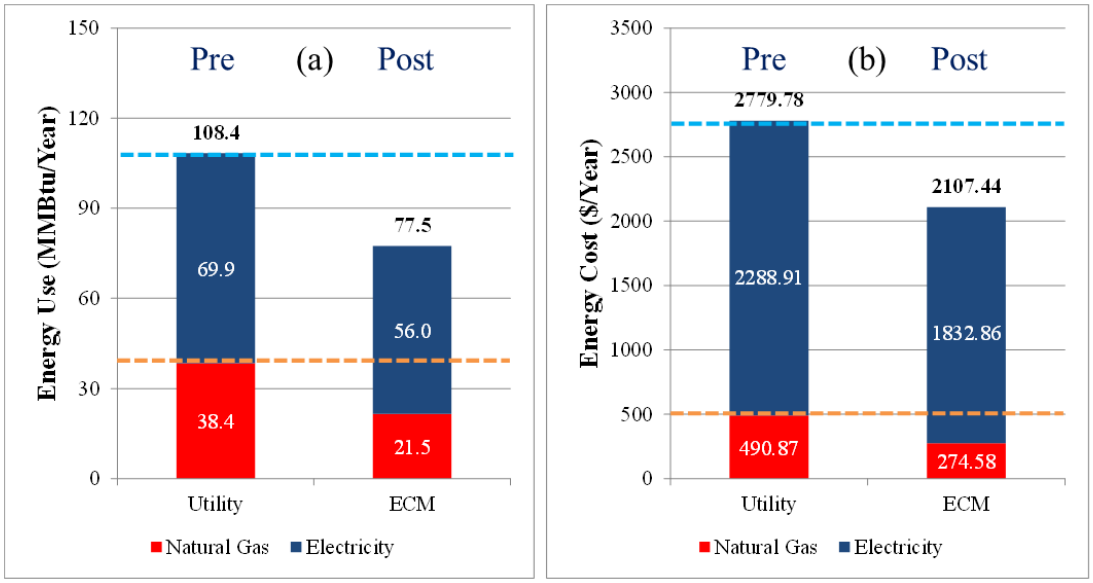


Figure 5.121 (a) Annual Energy Savings and (b) Energy Cost Savings by the Selected ECMs for the Case-study House #1 (7.1 Year of Pay-back ECM: Improving EF from 0.31 to 0.59; Improving SEER from 9.6 to 13.0; Improving Duct Sealing from 0.1 to 0.028)

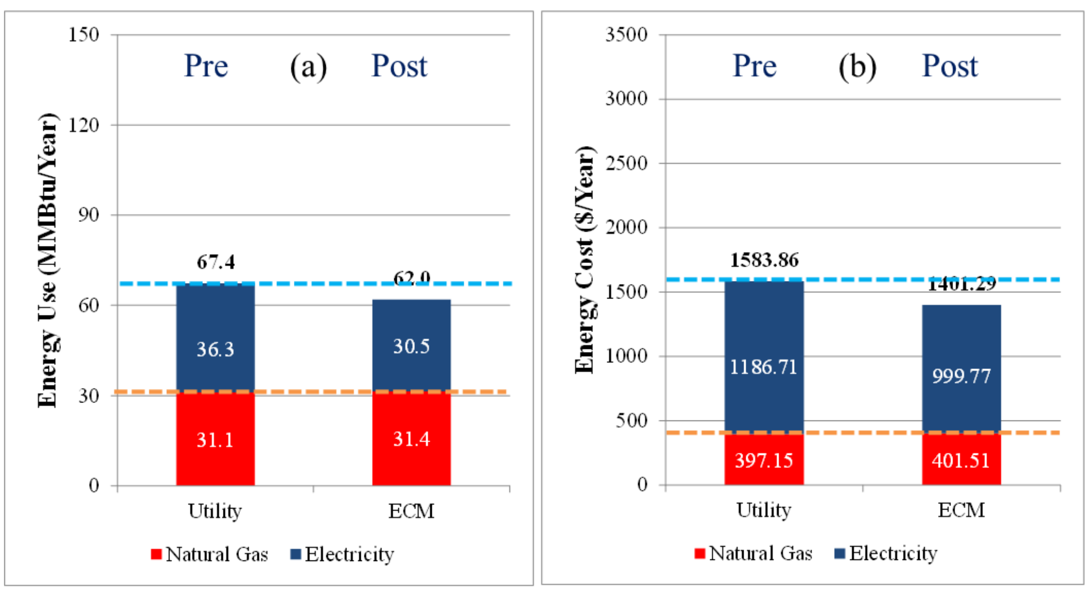


Figure 5.122 (a) Annual Energy Savings and (b) Energy Cost Savings by the Selected ECM for the Case-study House #2 (3.4 Year of Pay-back ECM: Improving Supply Duct Sealing from 0.13 to 0.028 and Return Duct Sealing from 0.09 to 0.028)

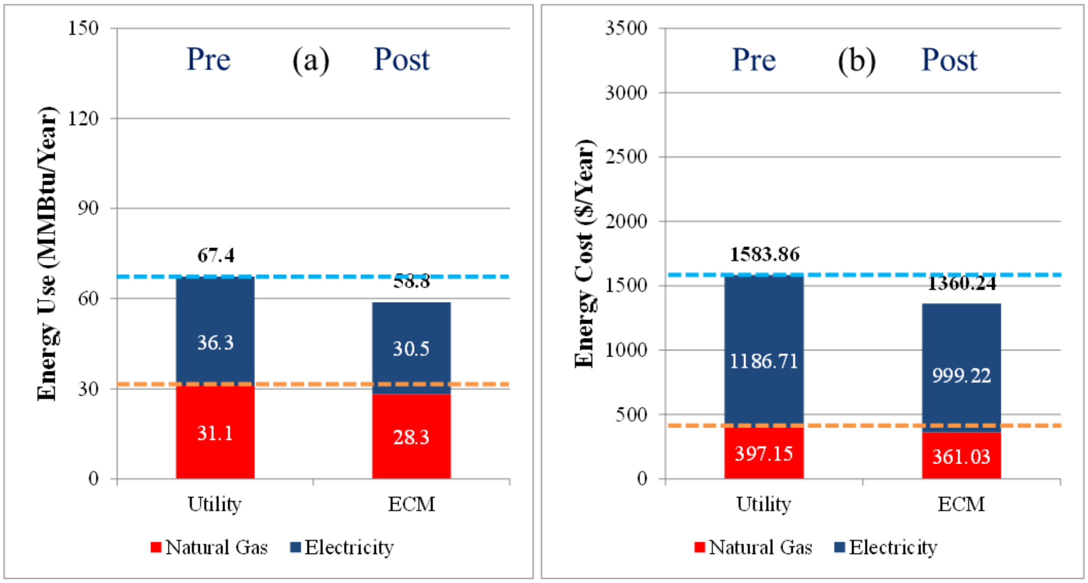


Figure 5.123 (a) Annual Energy Savings and (b) Energy Cost Savings by the Selected ECM for the Case-study House #2 (9.9 Year of Pay-back ECM: Improving EF from 0.50 to 0.59; Improving Supply Duct Sealing from 0.13 to 0.028 and Return Duct Sealing from 0.09 to 0.028)

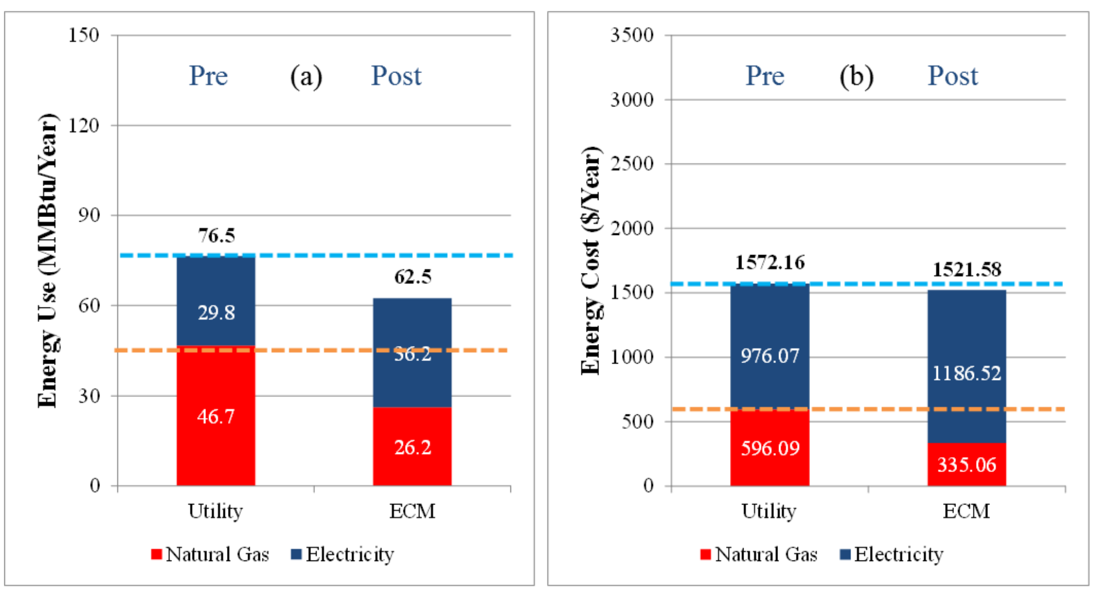


Figure 5.124 (a) Annual Energy Savings and (b) Energy Cost Savings by the Selected ECM for the Case-study House #3 (8.6 year of Pay-back ECM: Improving Envelope Sealing from 0.42 to 0.35)

CHAPTER VI

SUMMARY AND FUTURE WORK

A methodology for analyzing existing single-family residential energy use was developed and described in this study. This methodology can allow home energy auditors or homeowners who are not familiar with building energy analysis to evaluate the energy use of a house easily and accurately, and to determine energy conservation measures for the future retrofits. This methodology will contribute to the dissemination of energy efficient and cost effective improvements for existing houses in hot and humid climates.

6.1 Summary

A methodology to develop an accurate, consistent and easy-to-use, semi-automated home energy audit procedure for improvements in energy efficiency in an existing single-family house in a hot and humid climate has been described in this study. In order to accomplish this, three sequential methodologies were developed and demonstrated:

1) A methodology to enable the use of an easy-to-use residential simulation for a user who is not familiar with building energy simulation and HVAC systems or other residential systems;

2) A methodology that enables a semi-automatic, calibrated simulation using monthly utility bills for more accurate predictions of energy-efficient retrofits of a house; and
3) A methodology for determining the potential savings from energy conservation measures using either of the developed calibrated simulation.

In this study, three case-study houses were studied with the procedures. Case-study house #1 and a case-study house #2 were located in College Station, Texas, while case-study house #3 was located in Plano, Texas.

Case-study house #1 was a single-family house located in College Station, Texas. It was simulated using the detailed, as-built house information, the easy-to-use house information, and calibrated using the methodology developed in this study. After the calibration, the result of the easy-to-use calibrated simulation was compared with the results from the detailed, as-built calibrated simulation to verify the accuracy of using the easy-to-use simulation. The comparison shows that the global CV (RMSE) for the as-built and the easy-to-use calibrated simulations were 8.8% and 9.1%, respectively, which was a 0.3% difference between the two models. The CV (RMSE) for electricity and natural gas were also calculated as 6.8% and 7.6% for electricity, and 12.7% and 12.4% for natural gas use for the as-built calibrated simulation and the easy-to-use calibrated simulation respectively, which are differences of less than 1% between the both models.

In addition, the resultant parameters for the as-built calibrated simulation and the easy-to-use calibrated simulation were compared. From the comparison, it was found that the most influential parameters for the detailed, calibrated simulation for the case-study house #1 were the Lighting and Equipment (L&E) and the Energy Factor (EF). The final values for these parameters were close between the two models with differences of 7.3% for the L&E and 9.7% for the EF. Some of the other parameters had approximately a 10% differences between the models. However, the overall differences, which were evaluated using a global CV (RMSE) between the two models, were within 1.0%, so the other parameters were determined to be less significant parameters for the calibrations. The comparison of calibrated, detailed as-built simulation parameters with the easy-to-use simulation parameters showed that the easy-to-use simulation yielded similar results as the as-built simulation using the calibration methodology developed in this thesis.

In the next step the potential energy conservation measures for the case-study house #1 were determined. In a similar fashion to the step for the calibration, the as-built calibrated simulation and the easy-to-use calibrated simulation were both evaluated. To begin, the calibrated parameters for both simulations were compared with the parameters from the standard house, which is compliant with the 2009 IECC. In this comparison, the parameters that were less energy efficient than the standard house were selected as potential energy conservation measures for the case-study house #1. Each measure and combination of measures were then simulated and compared with the current utility energy use to calculate savings. In addition, a simple pay-back calculation was performed to find the most energy efficient and cost effective measures, with pay-back periods of less than 10 years. Using this procedure, the most energy efficient and cost effective potential ECMs from the detailed, as-built and easy-to-use simulations were determined to be: an improved EF for the domestic water heater; improved duct leakage; a combination of an improved EF and improved supply and return duct leakage; and a combination of improved EF, improved SEER for the A/C and improved duct leakage. The EF measure had a 4.9 year pay-back as determined by the detailed, as-built calibrated simulation, and had a 4.9 year pay-back from the easy-to-use calibrated simulation. The duct leakage measure had a 3.4 year pay-back as determined by the detailed, as-built calibrated simulation, and had a 2.1 year pay-back from the easy-to-use calibrated simulation. The combination of the EF and the duct leakage measure had a 4.0 year pay-back as determined by the as-built calibrated simulation, and had a 3.8 year pay-back from the easy-to-use calibrated simulation. The combination of the EF, the SEER and the duct leakage measure had a 7.7 year pay-back as determined by the detailed, as-built calibrated simulation, and had a 7.1 year pay-back from the easy-to-use calibrated simulation.

Case-study house #2 was also a single-family house located in College Station, Texas. It was simulated using only the easy-to-use house information, and calibrated using the methodology developed in this study. For the measured energy use data, one year of monthly utility billing data for electricity and natural gas were used. In the initial simulation, a global CV (RMSE) of 47.8% was accomplished. This included a 40.7% CV (RMSE) for the electricity and a 64.9% CV (RMSE) for the natural gas. After the calibration process was applied, a global CV (RMSE) of 17.2% was accomplished with 14.2% CV (RMSE) for the electricity and 20.6% CV (RMSE) for the natural gas.

After the calibration, the potential energy conservation measures for the case-study house #2 were determined. In this step, the calibrated parameters for the easy-to-use simulations were compared with the parameters that were modeled using a standard house that is compliant with the 2009 IECC. The calibrated parameters that were less energy efficient than the parameters for the standard house were selected as candidates for the potential measures for the case-study house #2. Some of the candidates for the measures were dropped from the ECM list since they were not energy efficient enough. The final potential measures for case-study house #2 were an improved EF for the DHW, improved return duct leakage and supply duct leakage, an improved infiltration rate, roof R-value and SHGC. Each measure and combination of measures (i.e., the combination of measures included the building envelope and fenestration, HVAC systems and all of measures) were simulated to identify energy savings and energy cost savings. Finally, a simply-payback period was calculated for the selected potential measures. The improved supply & return duct sealing, and the combination of an improved EF and improved duct sealing for the case-study house #2 were selected as the most energy efficient and cost effective measures, which had a 3.4 year pay-back period and 9.9 year pay-back period, respectively.

Case-study house #3 is a single-family house located in Plano, Texas. It was simulated using the easy-to-use house information, and calibrated using the methodology developed in this study. For measured energy use data, one year of monthly utility billing data for electricity and natural gas was used. In the initial simulation, a 79.2% global CV (RMSE), 77.2% CV (RMSE) for the electricity and 74.4% CV (RMSE) for the natural gas were accomplished. These were then improved using the calibration procedure to be a 18.3% global CV (RMSE), a 12.3% CV (RMSE) for the electricity and a 19.9% CV (RMSE) for the natural gas.

After the calibration, the potential energy conservation measures for case-study house #3 were determined. In this step, the calibrated parameters for the easy-to-use simulations were compared with the parameters from a standard house that is compliant with the 2009 IECC. The calibrated parameters that were less energy efficient than the parameters for the standard house were selected as candidates for the potential measures for the case-study house #3. Some of the candidates for the measures were dropped from the list since they were not energy efficient enough. The final potential measure for the case-study house #3 included the improved infiltration rate, which was simulated to calculate energy savings and energy cost savings.

Next, the simple pay-back calculation for the selected potential measure was performed for the case-study house #3. This measure was then determined to be the most energy efficient and cost effective measure, which had an 8.6 year pay-back period.

In summary, the energy savings and energy cost savings measures for the three test houses were determined using the most energy efficient and cost effective measures determined by simple pay-back period calculations. Annual energy savings and energy cost savings for the case-study house #1 included improving the DHW EF was 17 MMBtu/year and $222 per year respectively. This was accomplished by improving duct sealing, which saved 3.5 MMBtu/year and $261 per year respectively. In addition, improving the DHW EF and duct sealing saved 24 MMBtu/year and $458 per year respectively. And finally, the combination of improving the DHW EF, SEER and duct sealing saved 31 MMBtu/year and $672 per year. For case-study house #2, the measures were improving the duct sealing, which saved 5 MMBtu/year and $183 per year respectively, and improving the DHW EF and duct sealing, which saved 9 MMBtu/year and $224 per year respectively. For case-study house #3, the measures were improving the envelope sealing which saved 14 MMBtu/year and $51 per year, respectively.

6.2 Future Work

The limitations of this study, which were discussed in Section 3.2, and the recommendations for further research can be summarized as follows:

1) Expand the new home energy audit methodology to the other type of residences such as multi-family;
2) Expand the home energy audit methodology to climates other than the hot and humid climate of Texas;
3) Develop the home energy audit methodology for various other types of single-family houses such as houses with more than two-stories, foundations other than slab-on-grade, and energy sources other than electricity for cooling and natural gas for heating (i.e., all-electric households);
4) Expand cost analysis that includes life cycle cost of measures; and
5) Improve the calibrated simulation procedure to be more automatic.

In addition, other than the study limitations, future research should be developed to improve the methodology as follows:

6) Develop a more detailed calibration procedure taking account of occupant behavior for weekdays and weekends;
7) Develop a more detailed calibration procedure taking account of energy efficient measures for lighting and equipment, and consider HVAC operation schedules (i.e., intermittent or part-time) for weekdays and weekends;
8) Further develop the calibration methodology using hourly utility billing data (i.e., smart meter data) rather than monthly utility billing data;
9) Further develop the sensitivity analysis using 4P regression model instead of 3P regression model; and
10) The methodology developed in this study needs to be verified by more case-study houses, and the recommended ECMs need to be confirmed by a walk-through audit.

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APPENDIX A

APPROVALS OF THE RESEARCH COMPLIANCE AND BIOSAFETY'S HUMAN SUBJECTS PROTECTION PROGRAM FROM THE INSTITUTIONAL REVIEW BOARD (IRB)

Appendix A includes approval for this study from the Institutional Review Board (IRB) for the research compliance and biosafety's human subject's protection program. The IRB approval for the monthly utility bills and other information obtained from clipboard survey of case study houses is shown in Figure A.1.

DIVISION OF RESEARCH

Office of Research Compliance and Biosafety

TEXAS A&M UNIVERSITY

APPROVAL DATE:	02/11/2013
MEMORANDUM	
TO:	Jeff Haberl
	TAMU - College Of Architecture - Architecture
FROM:	Dr. James Fluckey Chair
	Institutional Review Board
SUBJECT:	Initial Review Submission Form Approval

Protocol Number:	IRB2012-0766
Title:	Development of an improved methodology for analyzing existing single-family residential energy use
Review Type:	Expedited
Approved:	02/11/2013
Continuing Review Due:	12/31/2014
Expiration Date:	01/31/2014
Review Categories and Regulatory Determinations:	Category 7: Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies
Document of Consent:	Waiver approved under 45 CFR 46.117 (c) 1 or 2/ 21 CFR 56.109 (c)1

This research project has been approved. As principal investigator, you assume the following responsibilities

1. **Completion Report:** Upon completion of the research project (including data analysis and final written papers), a Completion Report must be submitted to the IRB Office.
2. **Adverse Events:** Adverse events must be reported to the IRB Office immediately.
3. **Deviations:** Deviations from protocol must be reported to the IRB office immediately.
4. **Amendments:** Changes to the protocol must be requested by submitting an Amendment to the IRB Office for review. The Amendment must be approved by the IRB before being implemented.

This electronic document provides notification of the review results by the Institutional Review Board.

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Figure A.1 IRB Approval for the Monthly Utility Bills and Other Information Obtained from Clipboard Survey of Case Study Houses (IRB2012-0766)

APPENDIX B

ACRONYMS

Appendix B includes acronyms used in this dissertation.

ACEEE	American Council for an Energy-Efficient Economy
AHAM	Association of Home Appliance Manufacturers
AHRI	Air Conditioning, Heating, and Refrigeration Institute
AIM	Assess, Improve, and Measure
ANN	Artificial Neural Network
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASME	American Society for Mechanical Engineers
BEERS	Building Energy-Efficiency Rating System
BESTEST	Building Energy Simulation Test
BESTEST-EX	Building Energy Simulation Test for Existing Homes
BTP	Building Technologies Program
BWM	Box Whisker and Mean
CABO	Council of American Building Officials
CV	Constant Volume
CV (RMSE)	Coefficient of Variation of the Root Mean Squared Error
DD	Dual Duct

DDP	DOE-2 Desktop Processor
DHW	Domestic Hot Water
ECM	Energy Conservation Measure
EF	Energy Factor
EGRID	Emissions and Generation Resource Integrated Database
EIA	Energy Information Administration
EISA	Energy Independence and Security Act
EPACT	Energy policy Act
EPCA	Energy Policy and Conservation Act
ESL	Energy Systems Laboratory
FEMP	Federal Energy Management Program
FSEC	Florida Solar Energy Center
GAMA	Gas Appliance Manufacturers Assocation
HERS	Home Energy Rating System
HES	Home Energy Saver
HVAC	Heating, Ventilation, and Air Conditioning
IBPSA	International Building Performance Simulation Association
ICC	International Code Council
ICEBO	International Conference for Enhanced Building Operations
IEA	International Energy Agency
IECC	International Energy Conservation Code
IMT	Inverse Modeling Toolkit

IPMVP	International Performance Measurement and Verification Protocol
IRC	International Residential Code
L&E	Lighting and Equipment
LBNL	Lawrence Berkeley National Laboratory
LEED	Leadership in Energy and Environmental Design
M&V	Measurement and Verification
MBE	Mean Bias Error
MEC	Model Energy Code
MVR	Multi-Variable Regression
NAECA	National Appliance Energy Conservation Act
NAHB	National Association of Home Builders
NEAT	National Energy Audit Tool
NECPA	National Energy Conservation and Policy Act
NEMVP	North America Energy Measurement and Verification Protocol
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
PRISM	PRInceton Scorekeeping Method
RECS	Residential Energy Consumption Survey
RESNET	Residential Energy Services Network
RMSE	Root Mean Squared Error
SEC	Solar Energy Division

STEM	Short-Term Energy Monitoring
TBEPS	Texas Building Energy Performance Standards
TMY2	Typical Meteorological Year 2
TRY	Test Reference Year
TXHERO	Texas Home Energy Rating Organization
U.S. DOE	United States Department of Energy
USEPA	United States Environmental Protection Agency
USGBC	United States Green Building Council
VAV	Variable Air Volume
VBDD	Variable Based Degree Day
WWR	Window-to-wall Ratio

APPENDIX C

HISTORY OF THE U.S. ENERGY POLICIES, STANDARDS, GUIDELINES AND PROGRAMS

Appendix C includes the flow of history for the U.S. policies, standards, guidelines and programs regarding improving energy efficiency of buildings. Table C.1 presents the legislations relating to federal standard setting for energy efficiency, Table C.2 presents the standard, guideline and program for energy efficiency of existing buildings, and Figure C.1 and C.2 present chronological flow of the ASHRAE standards and the IECC for residential and commercial buildings.

Table C.1 The Legislation Relating to Federal Standard Setting for Energy Efficiency (Doris et al., 2009)

Name of Legislation	Year of Passage	Description	Legislative Reference
Energy Policy and Conservation Act (EPCA)	1975	Calls for establishment of energy conservation program and efficiency targets	Public Law 94-163
National Energy Conservation and Policy Act (NEPCA)	1978	Authorizes DOE to set mandatory standards for thirteen household products	Public Law 100-12
National Appliance Energy Conservation Act (NAECA)	1987	Establishes national standards for home appliances, and schedules regular updates through 2012	Public Law 100-357
Energy Policy Act 1992 (EPACT 1992)	1992	Expands standards to include additional commercial and residential appliances	Public Law 102-486
Energy Policy Act 2005 (EPACT 2005)	2005	Updates testing procedures for appliances	Public Law 109-58
Energy Independence and Security Act 2005 (EISA 2007)	2007	Expands standards to include additional appliances and updates some existing standards	Public Law 110-140

Table C.2 Standard, Guideline, and Program for Existing Buildings

Standard / Guideline / Program	Year	Title	Publisher
ASHRAE Standard 100-2006	2006	Energy Conservation in Existing Buildings	ASHRAE
ASHRAE Standard 105-2007	2007	Standard Methods of Measuring, Expressing and Comparing Building Energy performance	ASHRAE
ASHRAE Guideline 0-2005	2005	The Commisioning Process	ASHRAE
ASHRAE Guideline 1.1-2007	2007	The HVAC&R Techinical Requirements for the Comissioning Process	ASHRAE
LEED Reference Guide (Commercial)	2009	Green Building Operations & Maintenance Reference Guide	USGBC
Home Energy Rating System (Residential)	2006	2006 Mortgage Industry National Home Energy Rating Sysems Standards	RESNET

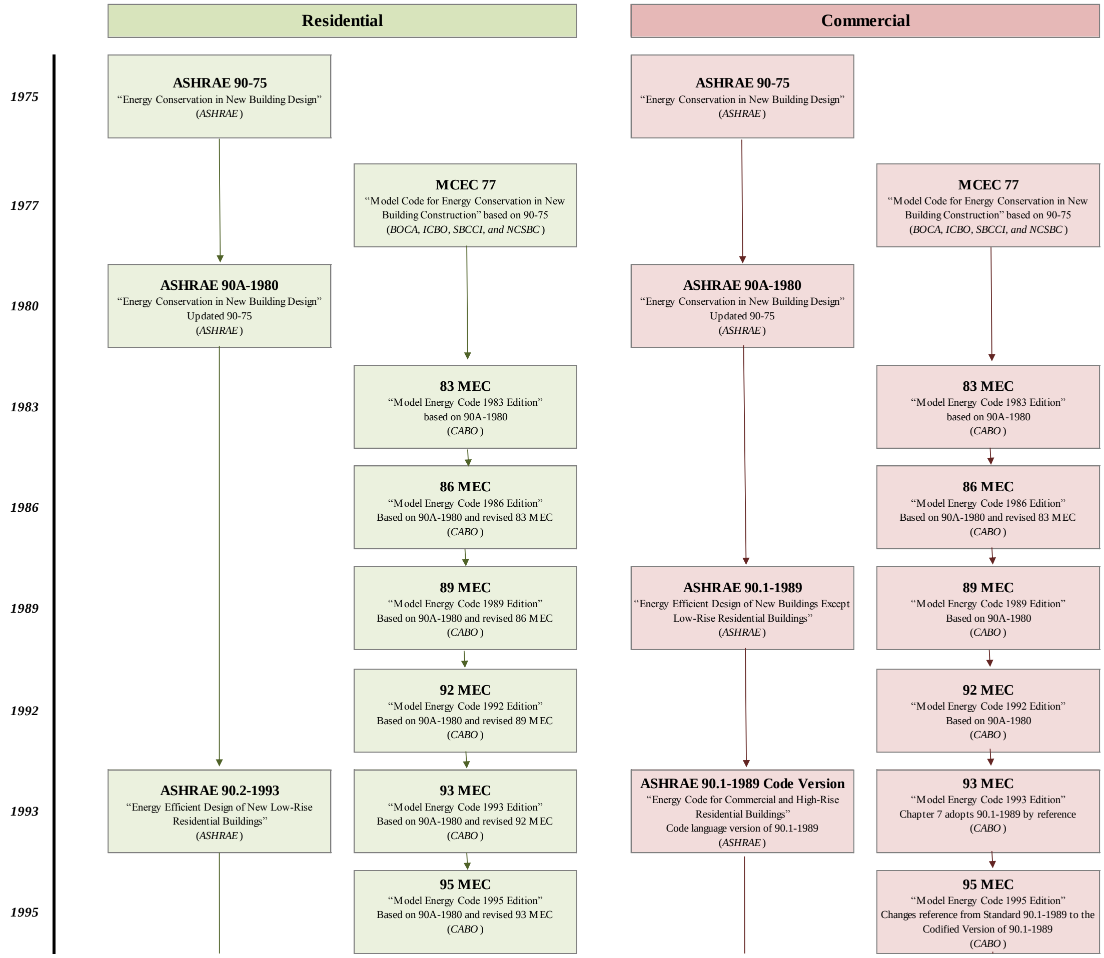


Figure C.1 ASHRAE Standards and IECC for Residential and Commercial (1975-1995)

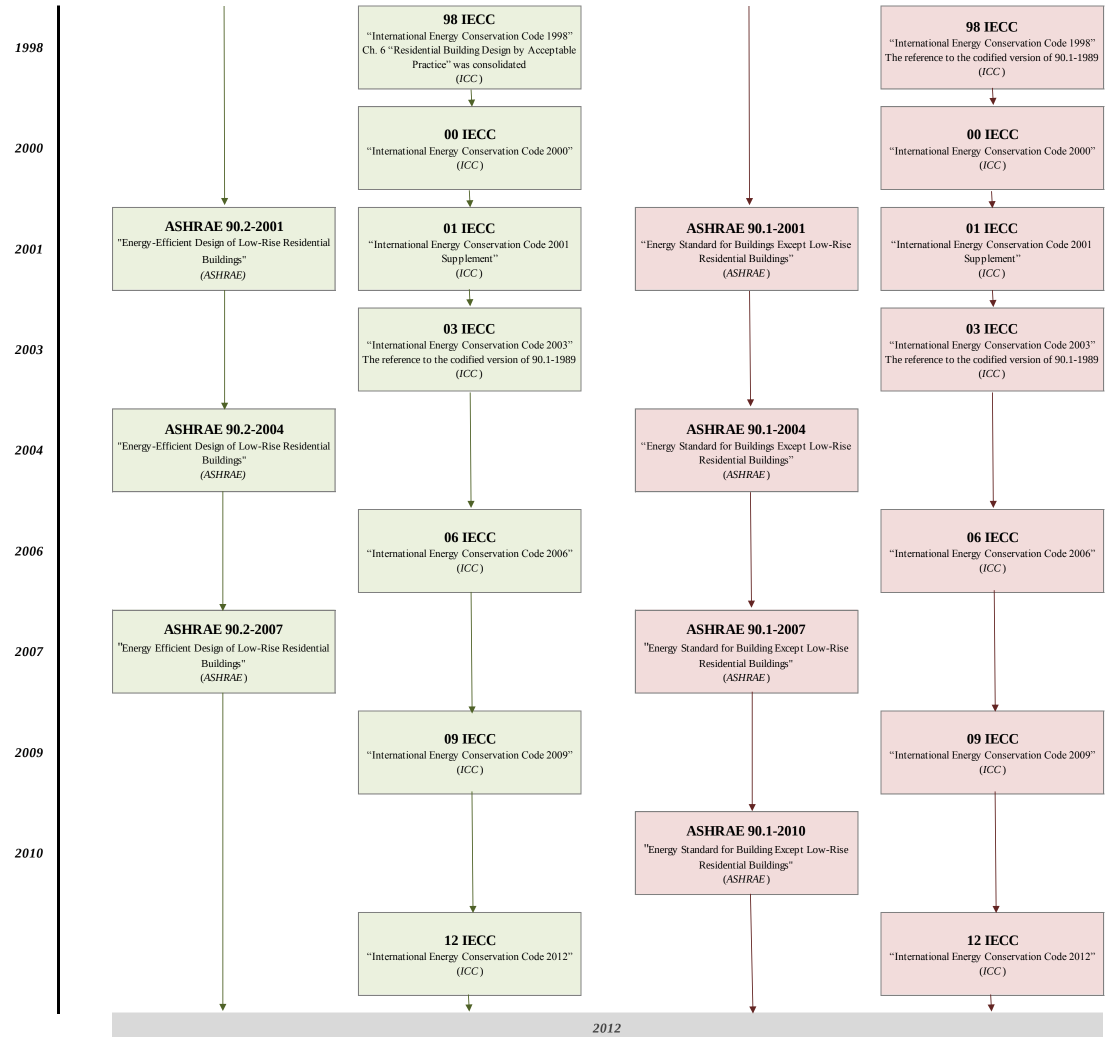
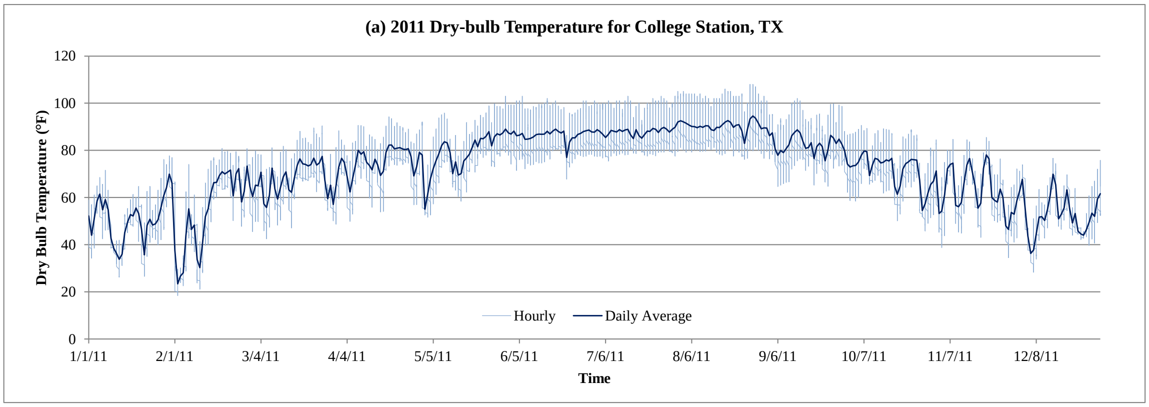


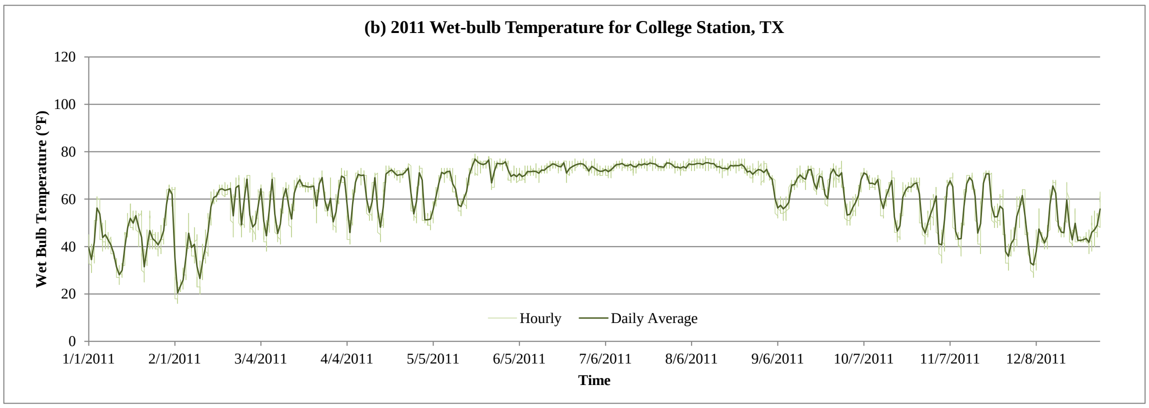
Figure C.2 ASHRAE Standards and IECC for Residential and Commercial (1998-2012)

APPENDIX D

WEATHER DATA IN TEXAS

Appendix D includes the weather data in TRY weather files used in this study. Figure D.1 presents 2011 TRY weather data, Figure D.2 presents 2012 TRY weather data and Figure D.3 presents 2013 TRY weather data for College Station, Texas, and Figure D.4 presents 2012 TRY weather data for Dallas, Texas. Each figure contains (a) dry-bulb temperature (°F), (b) web-bulb temperature (°F), (c) dew-point temperature (°F), (d) wind speed (knots), (e) global horizontal solar radiation (Btu/hr-ft^2) and (f) direct normal solar radiation (Btu/hr-ft^2).





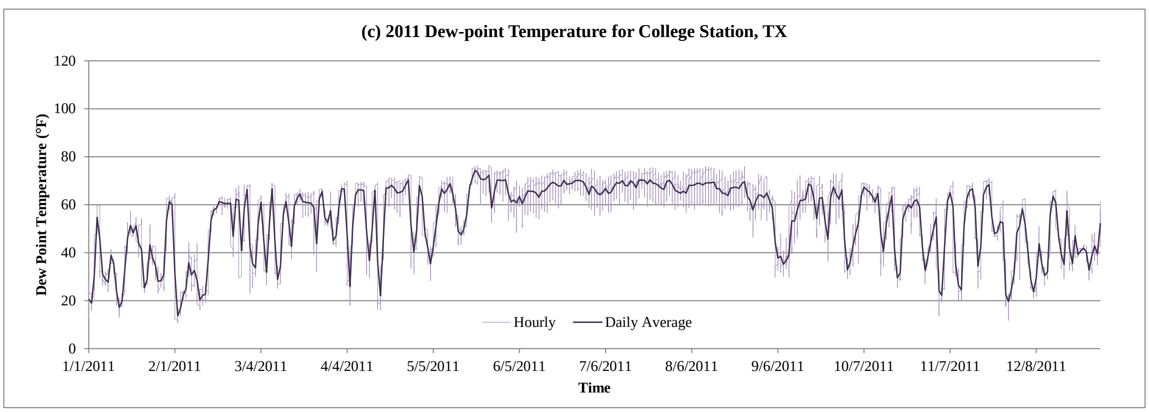
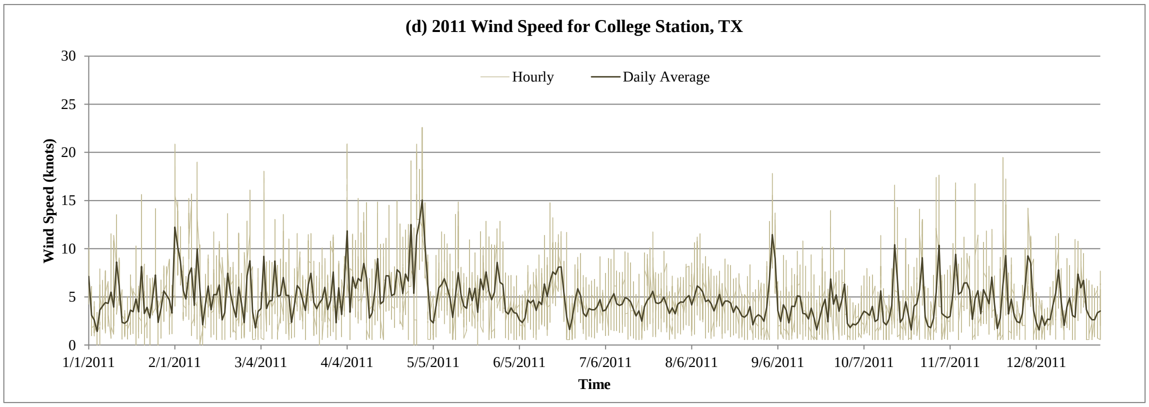
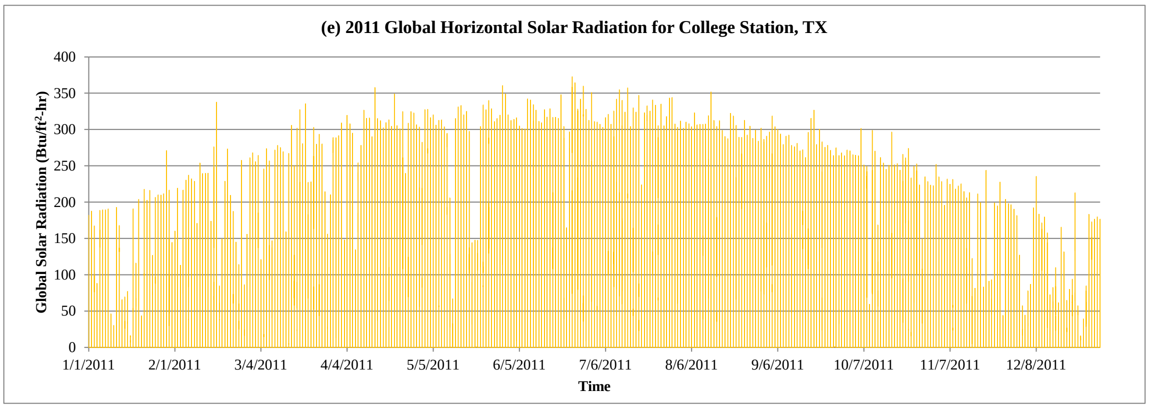
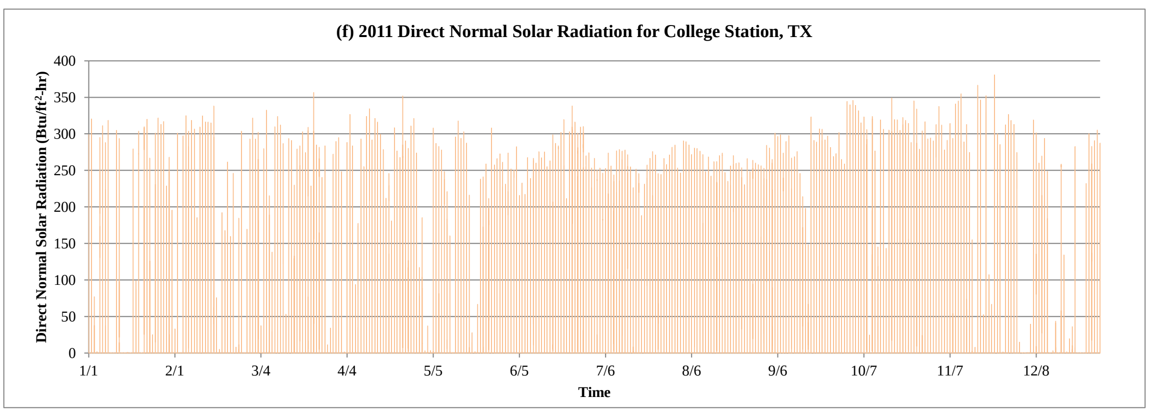


Figure D.1 Weather Data for 2011 College Station, Texas: (a) Dry-bulb Temperature, (b) Wet-bulb Temperature, (c) Dew-point Temperature, (d) Wind Speed, (e) Global Horizontal Solar Radiation and (f) Direct Normal Solar Radiation







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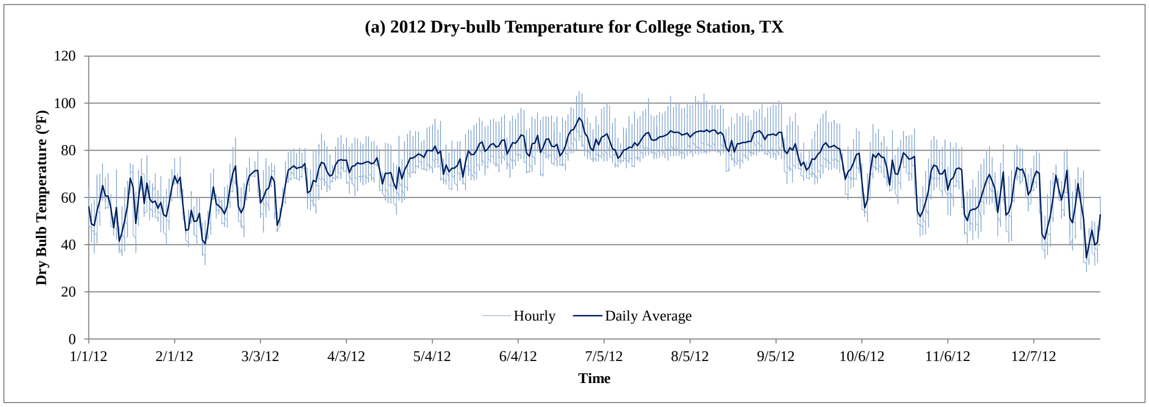
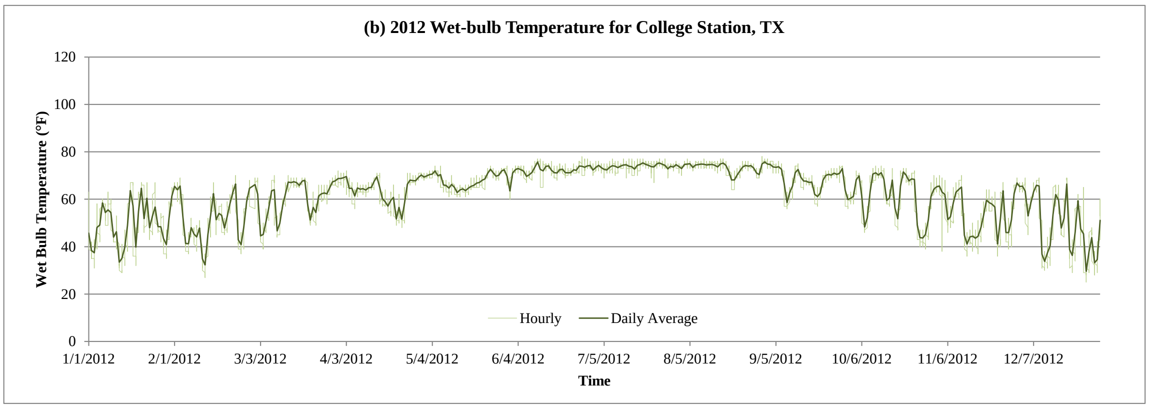




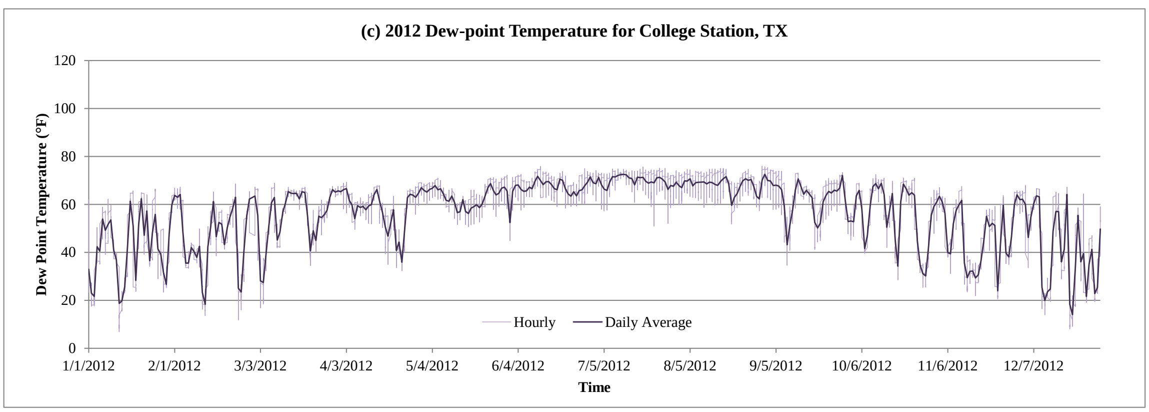
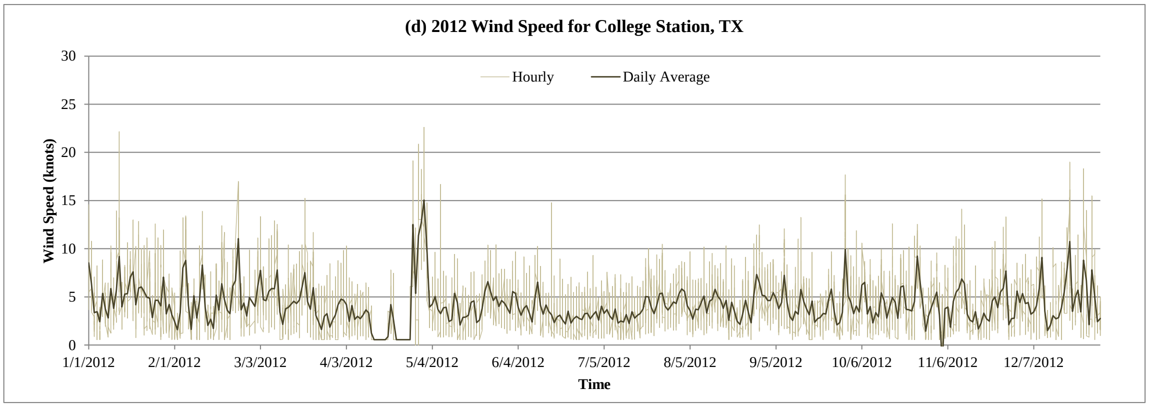
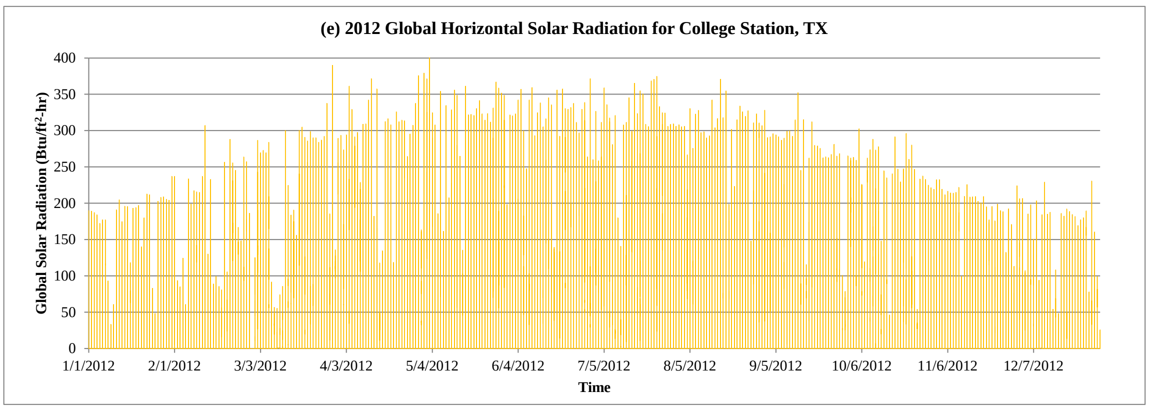
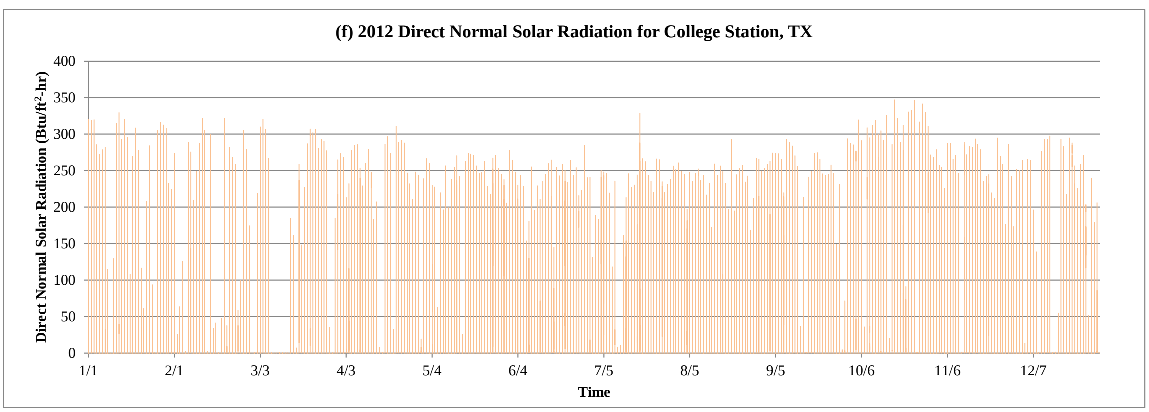


Figure D.2 Weather Data for 2012 College Station, Texas: (a) Dry-bulb Temperature, (b) Wet-bulb Temperature, (c) Dew-point Temperature, (d) Wind Speed, (e) Global Horizontal Solar Radiation and (f) Direct Normal Solar Radiation







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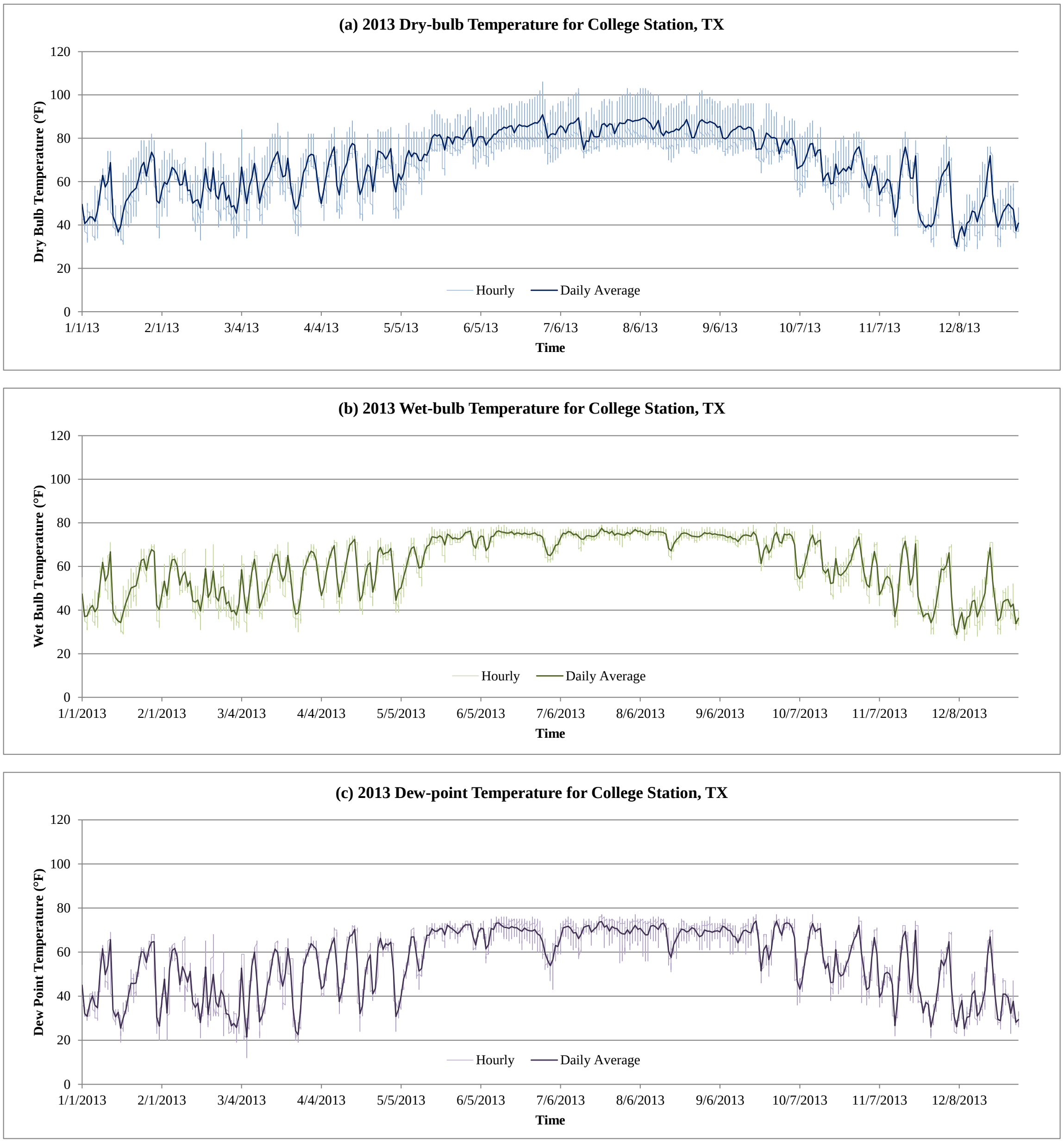
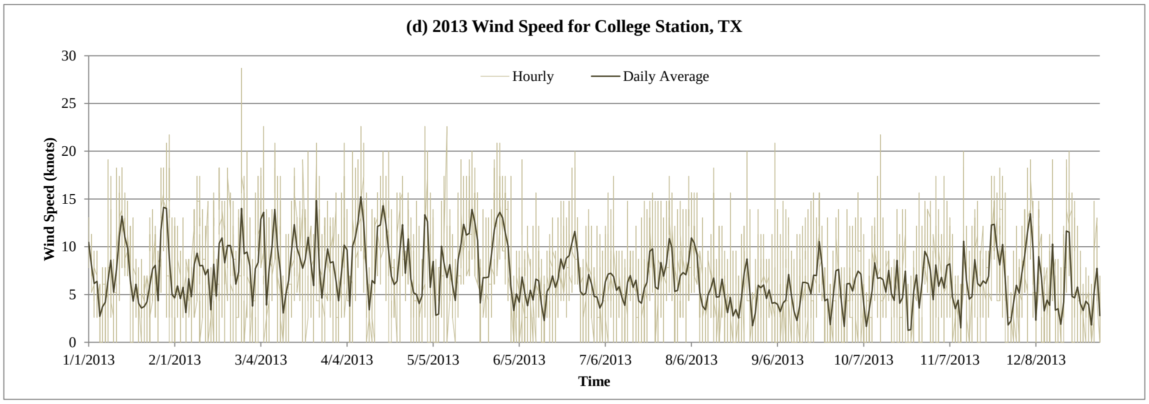
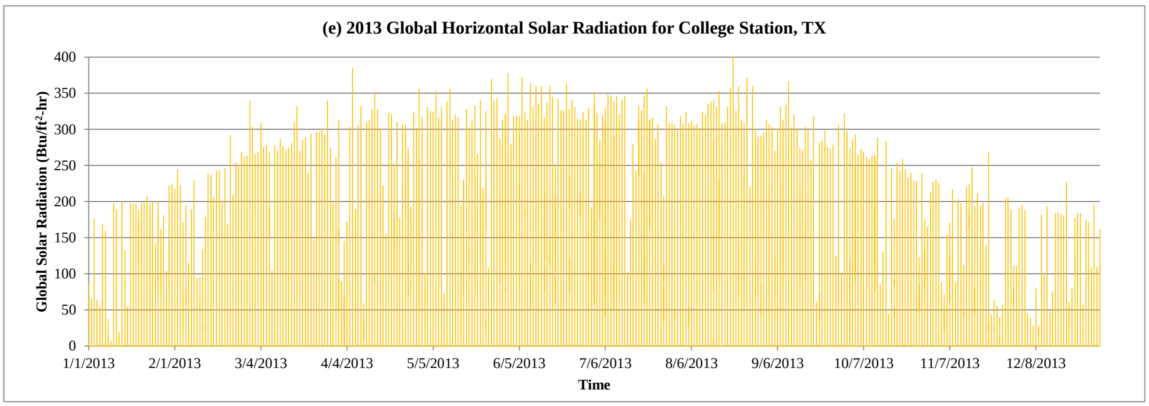
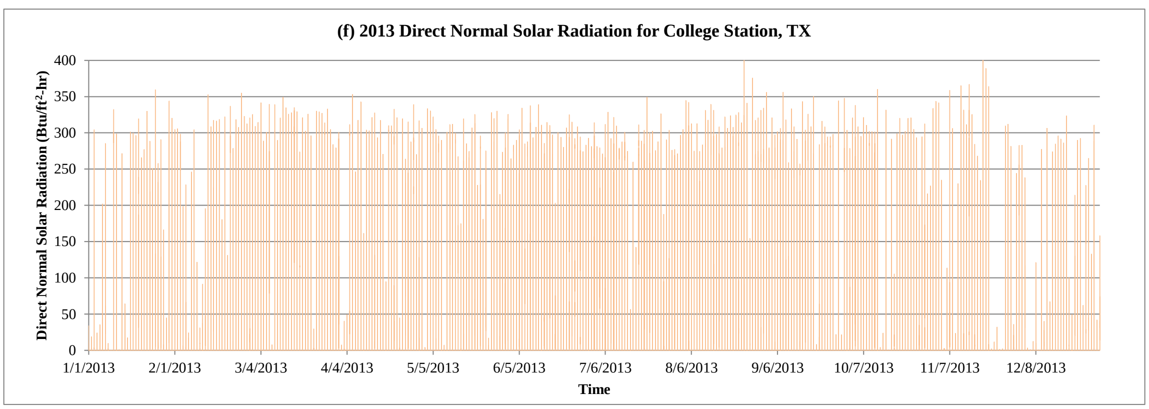


Figure D.3 Weather Data for 2013 College Station, Texas: (a) Dry-bulb Temperature, (b) Wet-bulb Temperature, (c) Dew-point Temperature, (d) Wind Speed, (e) Global Horizontal Solar Radiation and (f) Direct Normal Solar Radiation







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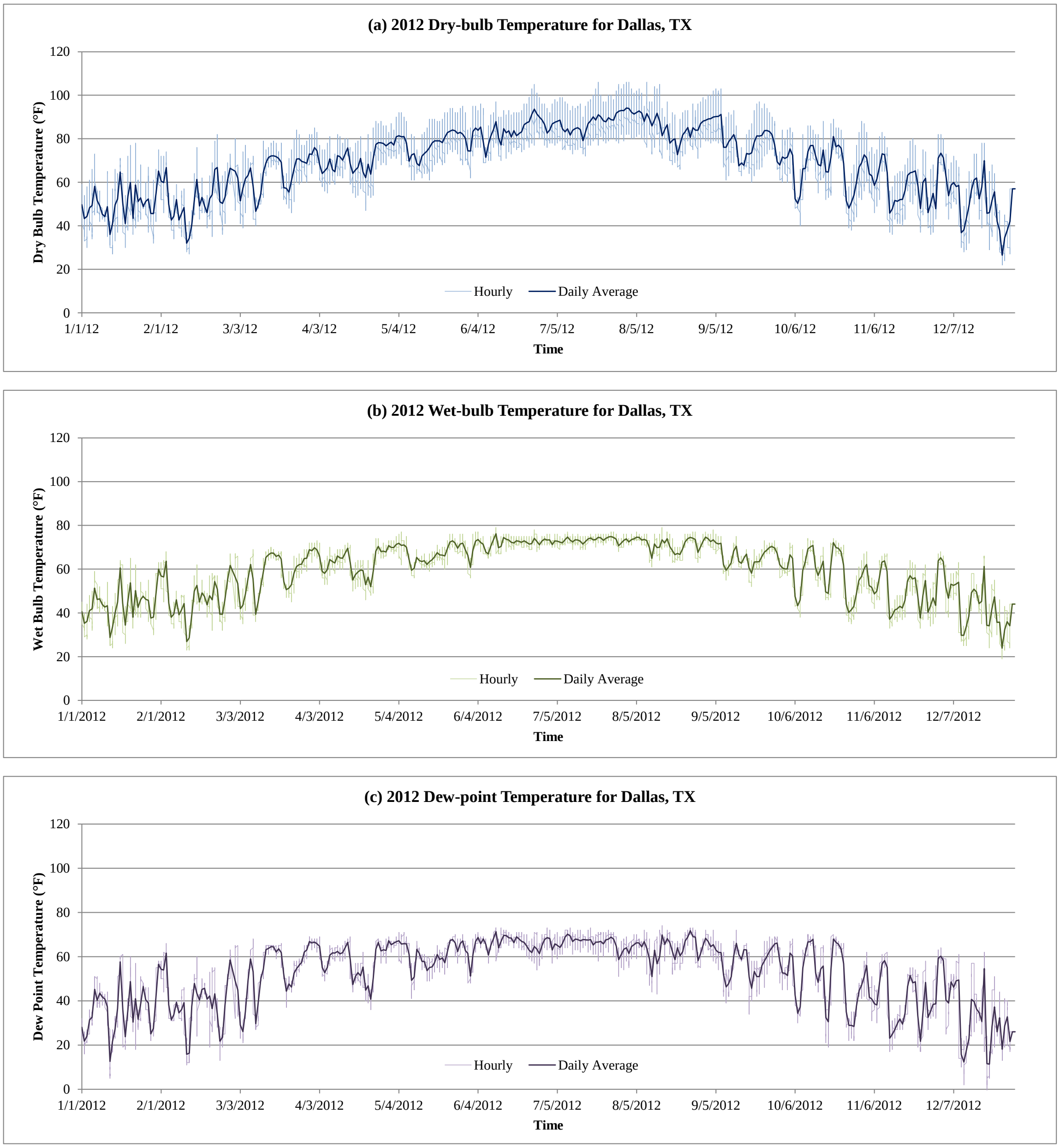
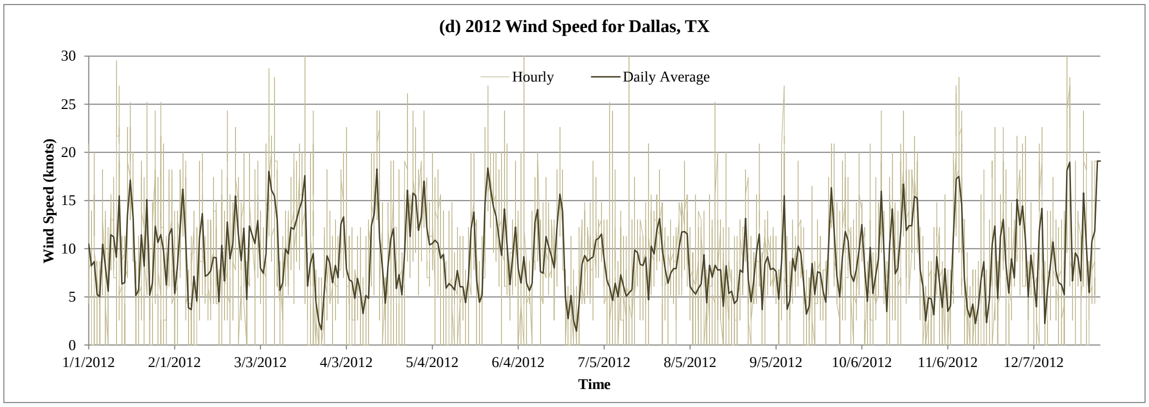
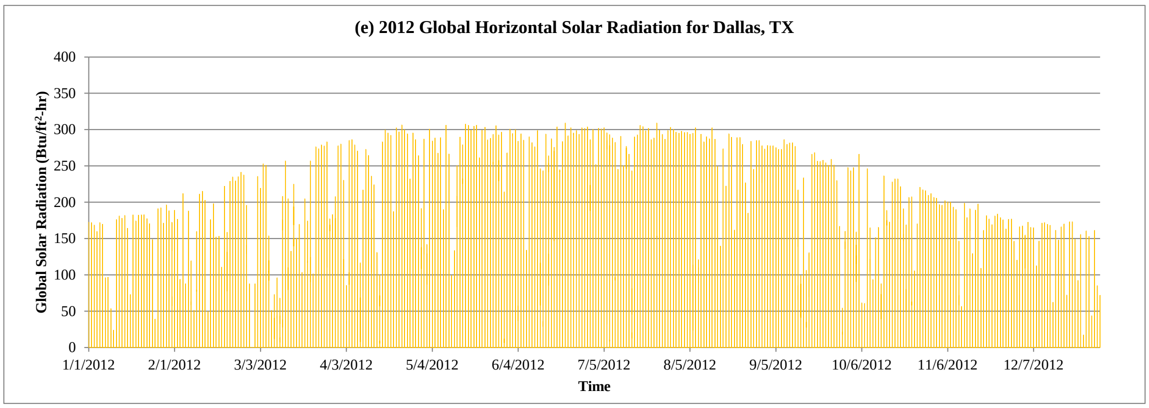


Figure D.4 Weather Data for 2012 Dallas, Texas: (a) Dry-bulb Temperature, (b) Wet-bulb Temperature, (c) Dew-point Temperature, (d) Wind Speed, (e) Global Horizontal Solar Radiation and (f) Direct Normal Solar Radiation





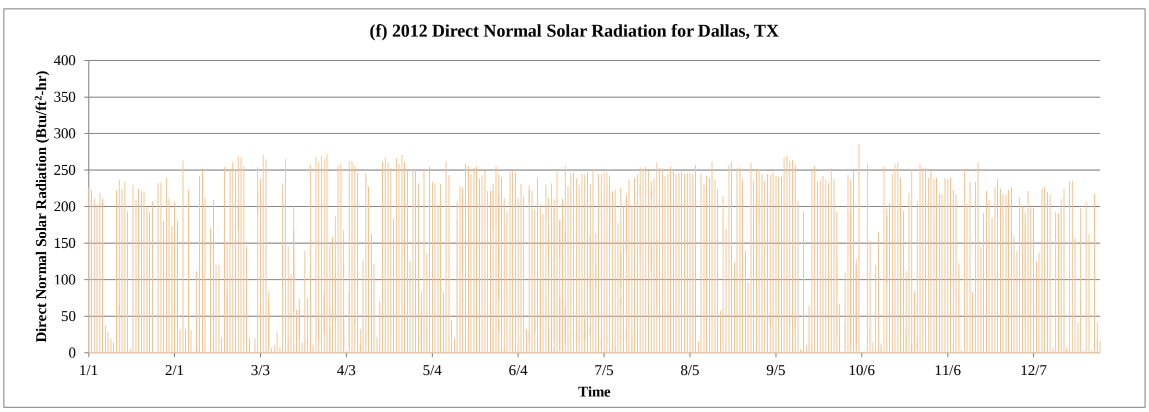


Figure D.4 Continued

APPENDIX E

CALCULATIONS FOR DIRECT NORMAL SOLAR RADIATION AND INTERPOLATION OF MISSING WEATHER DATA

Appendix E includes a calculation for direct normal solar radiation using measured global solar radiation, and filling-in the missing data in a weather data.

For a calculation for direct normal solar radiation using measured global solar radiation, Erbs correlation was used (Duffie and Beckman 2006). Direct normal solar radiation (I_b) was calculated as following equations (E.1) through (E.6):

$$\frac{I_d}{I} = 1.0 - 0.09K_T \qquad \text{For } K_T \leq 0.22 \qquad \text{(E.1)}$$

$$\frac{I_d}{I} = 0.9511 - 0.1604K_T + 4.388{K_T}^2 - 16.638{K_T}^3 + 12.336{K_T}^4$$

$$\text{For } 0.22 < K_T \leq 0.8 \qquad \text{(E.2)}$$

$$\frac{I_d}{I} = 0.165 \qquad \text{For } K_T > 0.8 \qquad \text{(E.3)}$$

Where K_T =Hourly clearness index = $\frac{I}{I_o}$,

I_d= Hourly diffuse solar radiation,

I = Hourly measured global solar radiation, and

I_o = Hourly extraterrestrial radiation

$$I_o \cong G_o = G_{SC}\left(1 + 0.033COS\frac{360n}{365}\right) \times (COS\emptyset COS\delta COS\omega + SIN\emptyset SIN\delta)$$

$$\text{(E.4)}$$

Where G_o = Hourly extraterrestrial radiation between sunrise and sunset,

G_{SC} = Solar constant (1,367 W/m^2),

n= n^{th} day of the year,

$\emptyset$ = Latitude in degree,

δ = Solar declination ($\delta = 23.45 \sin 360 \frac{284-n}{365}$) and

ω = Hourly angle at the midpoint of the hour in degree

$$I_d = \left(\frac{I_d}{I}\right) \times I \quad \text{(E.5)}$$

$$I_b = \left\{1 - \left(\frac{I_d}{I}\right)\right\} \times I \quad \text{(E.6)}$$

In addition, hourly weather data obtained from the NCDC, the TCEQ and solar test bench at Texas A&M University sometimes has missing data, and the missing data of certain weather parameters needs to be filled in before packing the weather file. In order to do that, the method suggested by Long (2006) was applied in this study. The hourly weather parameters that need to be filled-in are:

- Dry-bulb temperature in °F
- Wet-bulb temperature in °F,
- Dew-point temperature in °F,
- Global solar radiation in Btu/hr-ft^2,
- Direct normal solar radiation in Btu/hr-ft^2, and
- Station Pressure in inHg

For dry-bulb temperature, wet-bulb temperature, dew-point temperature, global solar radiation and direct normal solar radiation, missing data was filled-in by three different cases:

- When the length of missing gaps is equal or less than 6 hours: the missing data was filled-in by linear interpolation by following equation (E.7).

$$f(t_n) = f(t_1) + \left(\frac{f(t_2) - f(t_1)}{t_2 - t_1}\right) \cdot n \tag{E.7}$$

Where $f(t_n)$ = Time step to fill, and

$f(t_1)$ and $f(t_2)$ = The values around the missing time step

- When the length of missing gaps are larger than 6 hours and less than 48 hours: the missing data was filled-in by taking the trend of the first previous day that is valid as seen in following equation (E.8).

$$f(t_n) = f(t_{n-d}) + f(t_1) - f(t_{1-d}) + \left(\frac{f(t_2) - f(t_{2-d}) - \left(f(t_1) - f(t_{1-d})\right)}{t_2 - t_1 + 1}\right) \cdot n \tag{E.8}$$

Where $f(t_n)$ = The time step to fill,

$f(t_1)$ and $f(t_2)$ = The values around the missing time step, and

d = The offset back to the previous valid day

- When the length of missing gaps is equal or larger than 48 hours: the missing data was filled-in by data from nearby weather station, but there was no more than 48 hours gaps of weather data used in this study.

For station pressure, missing data was filled-in with last value previous to the gap. Finally for other weather parameters that is not mentioned above (i.e., wind speed, wind direction and precipitation), missing data was left in “999” value.

APPENDIX F

COSTS FOR UNIT AND INSTALLATION OF MEASURE COMPONENTS

Appendix E includes the costs for unit and installation of each energy conservation measure component used in this study. Table E.1 summarized the cost and product information for all measure components.

Table E.1 Unit and Installation Costs for Various Components

Component	Description	Total Cost[1]	Reference
Space Cooling Equipment[3]	5 tons / SEER 13	\$3,030.00/unit	Heat and Cool (2014) - *Klimaire A/C*
Hot water Heater[3]	50 gallon / 40000 Btu/hr / EF 0.63	\$1,100.00/unit	PexSupply.com (2014) - *Bradford White Water Heater*
Duct Leakage[2]	Improve Duct Sealing (0.028)	\$0.13/ft^2	Mukhopadhyay et al. (2013)
Fenestration	SGHC 0.25 / U-value 0.4	\$31.77/ft^2	Faithful+Gould (2012)
Roof Insulation	Blown-in Insulation R-38	\$1.33/ft^2	Faithful+Gould (2012)
Envelope Leakage[2]	Improve Envelope Sealing (0.35 ACH)	\$0.20/ft^2	Mendon et al. (2013)

Notes:
1. Costs inclusive of labor and equipment.
2. Incremental costs.
3. Assuming no charge in installation costs.

APPENDIX G

CALIBRATION PROCESS FOR EACH PARAMETER OF CASE-STUDY HOUSE #2

Appendixes G & H include minimum global CV (RMSE) changes for each parameter that was used in calibrations for the case-study house #2 and #3. Figure F.1 to Figure F.53 presents global CV (RMSE) changes for each parameter (a) in 0% to 100% scale in Y axis and (b) adjusted scale in Y axis for the case-study house #2, and Figure G.1 to Figure G.70 presents global CV (RMSE) changes for each parameter (a) in 0% to 100% scale in Y axis and (b) adjusted scale in Y axis for the case-study house #3.

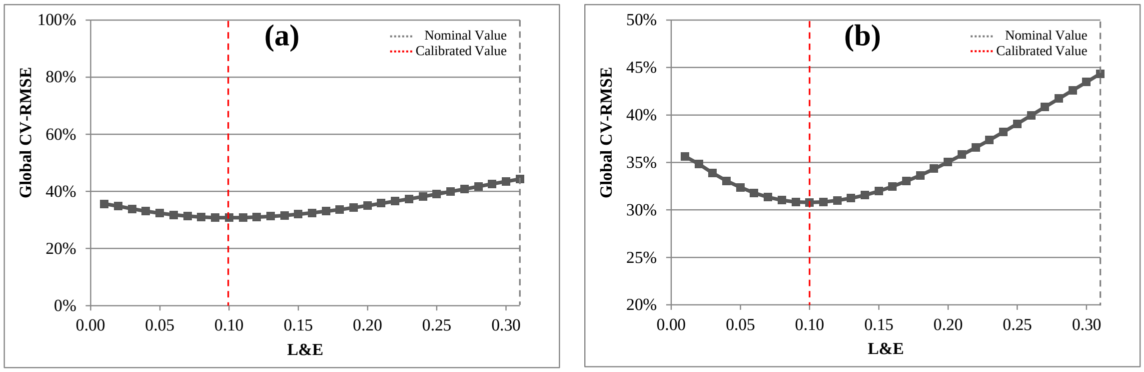


Figure F.1 Global CV (RMSE) Changes for L&E (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

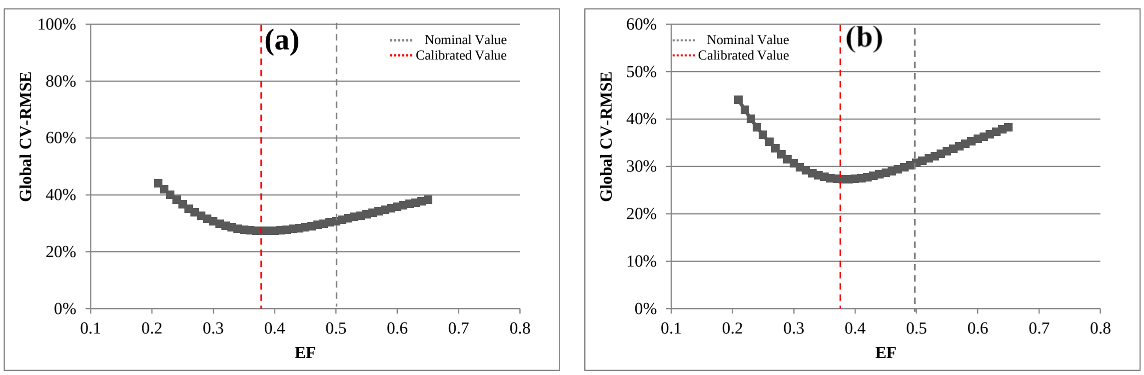


Figure F.2 Global CV (RMSE) Changes for EF (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

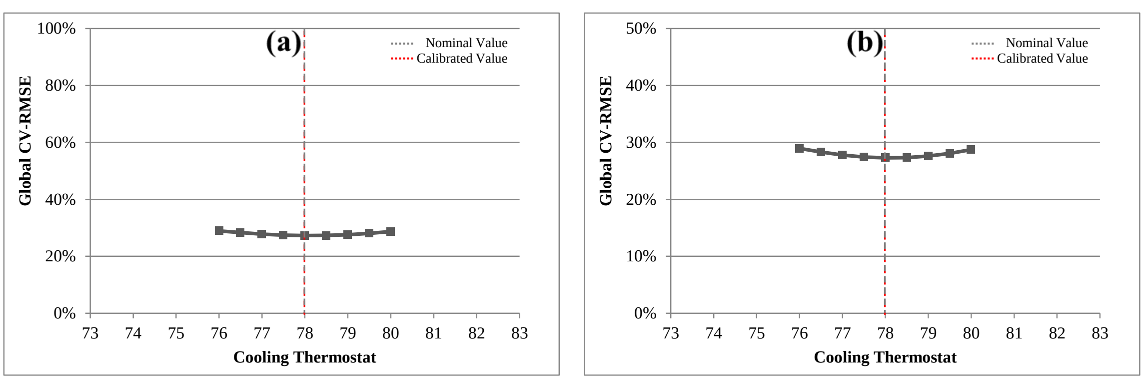


Figure F.3 Global CV (RMSE) Changes for Cooling Thermostat Setpoint Temperature (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

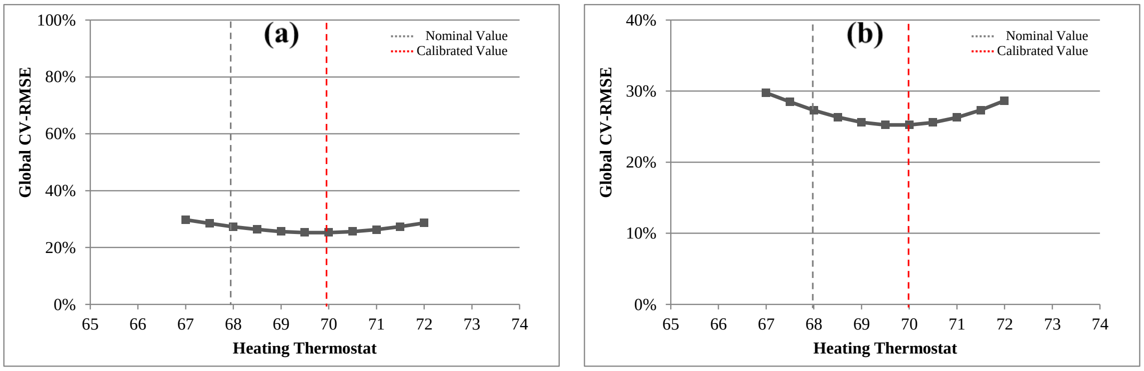


Figure F.4 Global CV (RMSE) Changes for Heating Thermostat Setpoint Temperature (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

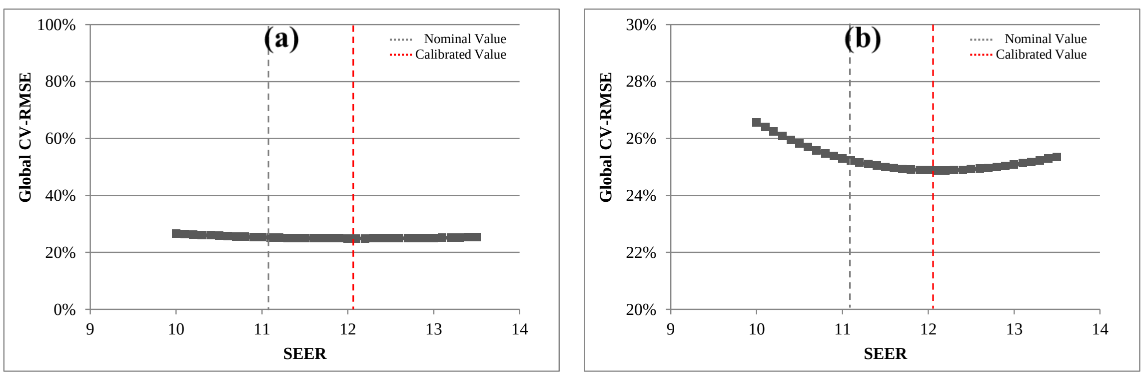


Figure F.5 Global CV (RMSE) Changes for SEER (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

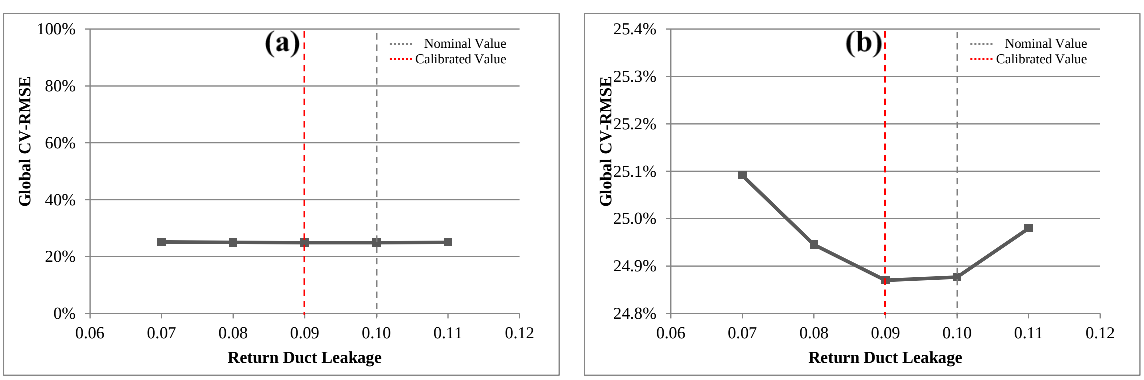


Figure F.6 Global CV (RMSE) Changes for Return Duct Leakage (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

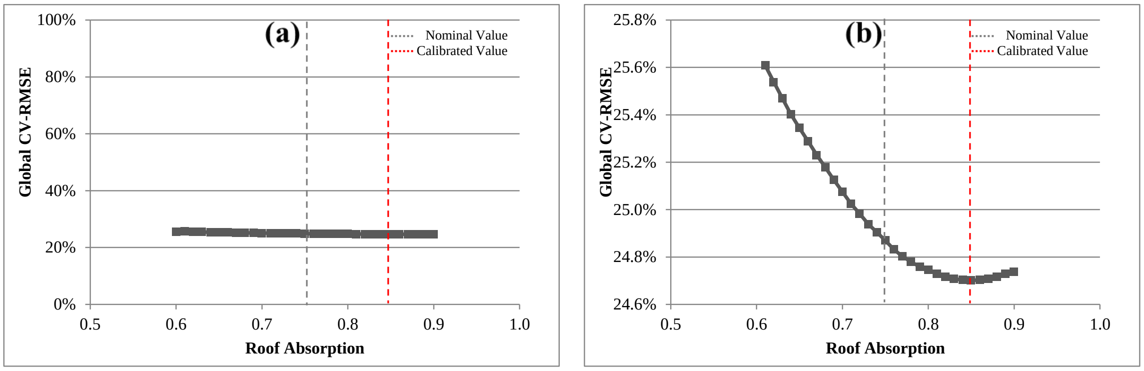


Figure F.7 *Global CV (RMSE) Changes for Roof Absorption (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

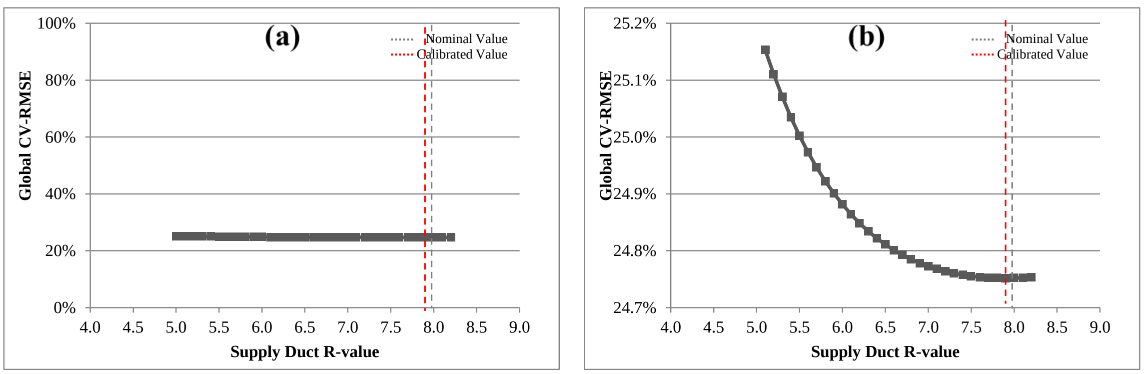


Figure F.8 *Global CV (RMSE) Changes for Supply Duct R-value (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

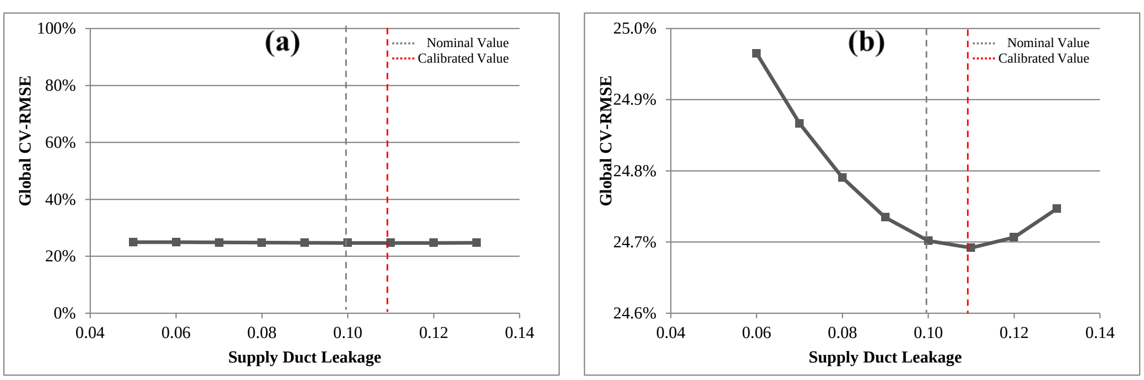


Figure F.9 *Global CV (RMSE) Changes for Supply Duct Leakage (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

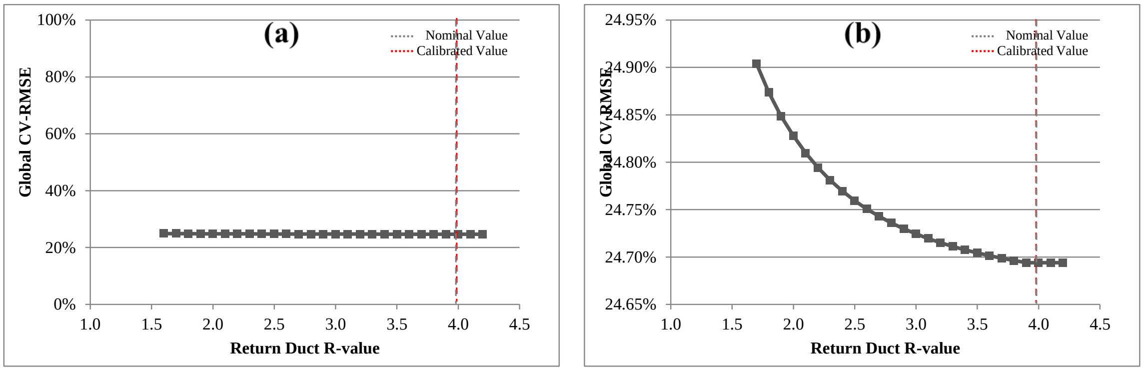


Figure F.10 Global CV (RMSE) Changes for Return Duct R-value (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

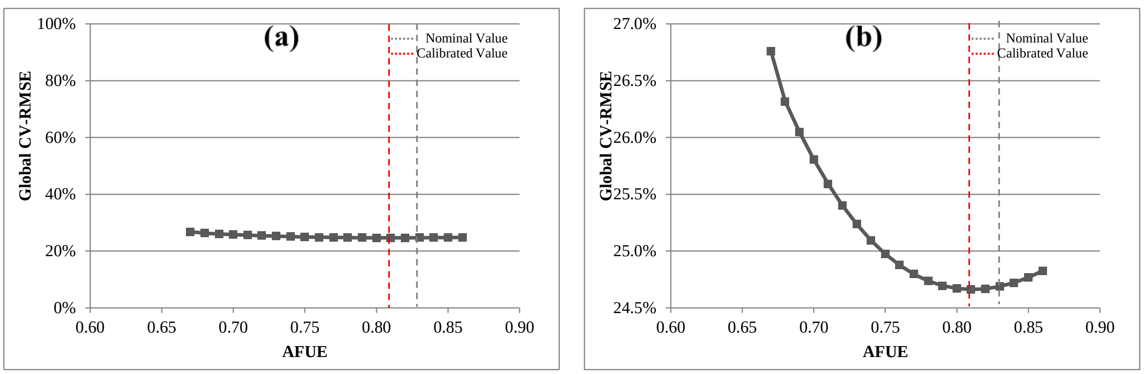


Figure F.11 Global CV (RMSE) Changes for AFUE (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

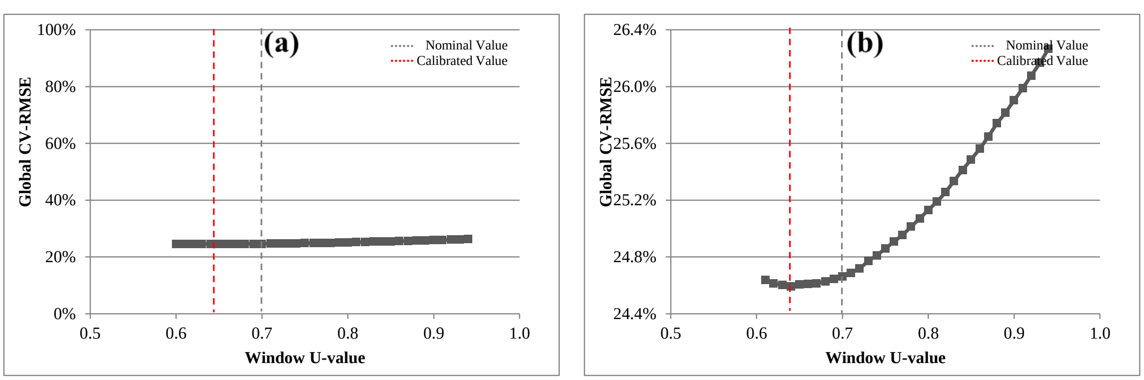


Figure F.12 Global CV (RMSE) Changes for Window U-value (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

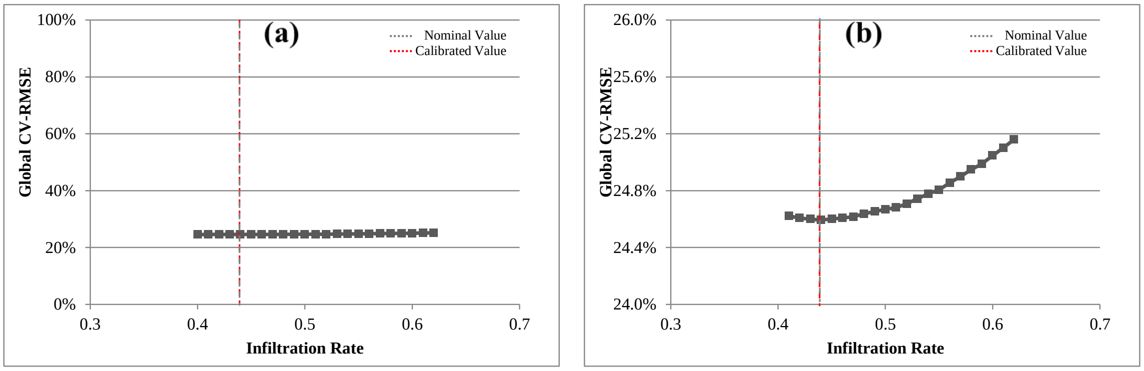


Figure F.13 *Global CV (RMSE) Changes for Infiltration Rate (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

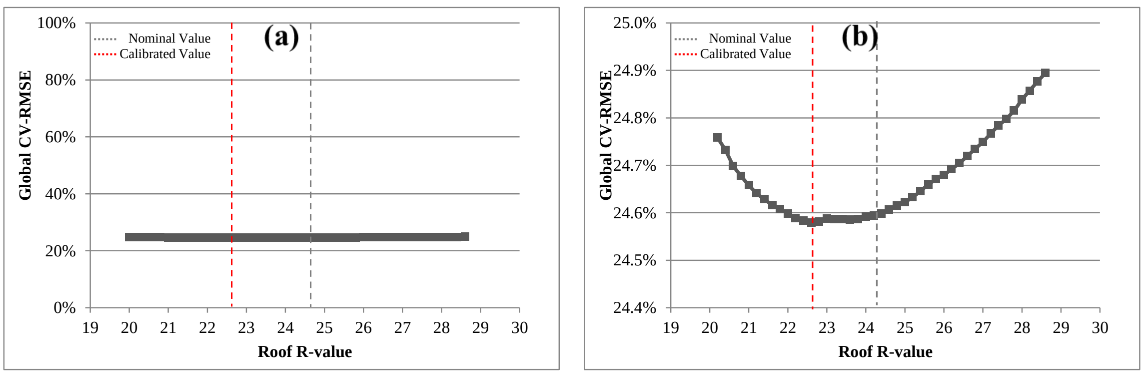


Figure F.14 *Global CV (RMSE) Changes for Roof R-value (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

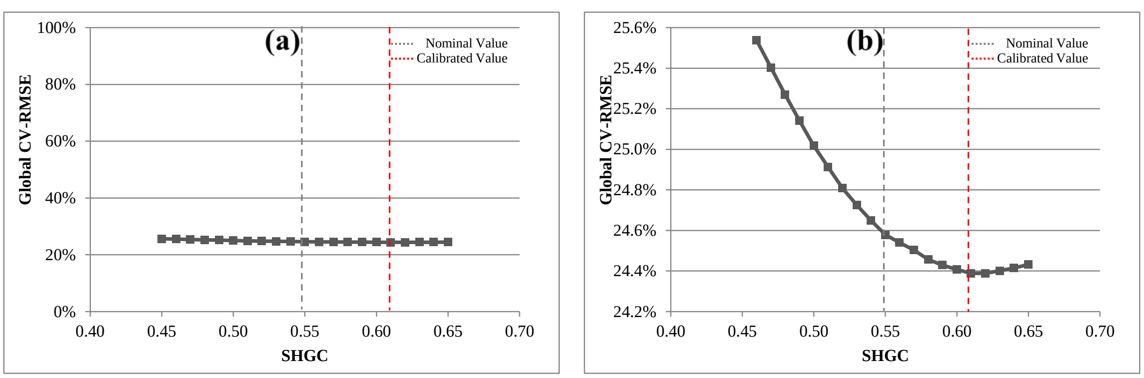


Figure F.15 *Global CV (RMSE) Changes for SHGC (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

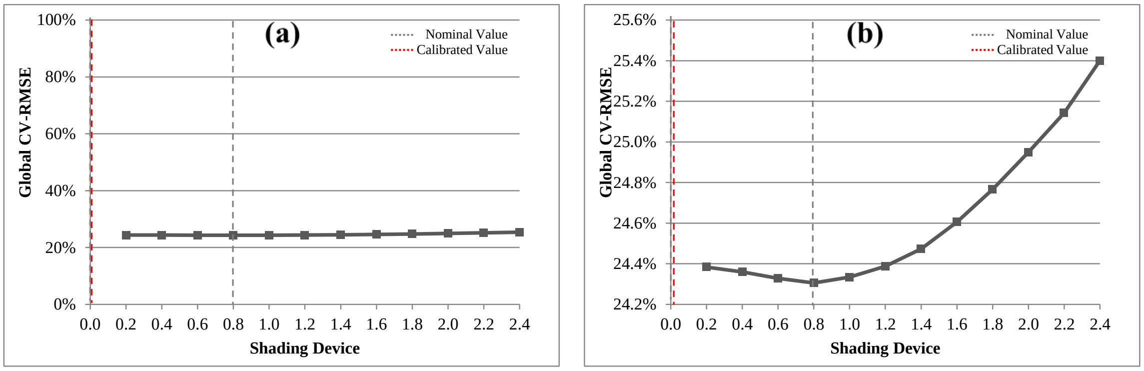


Figure F.16 *Global CV (RMSE) Changes for Shading Devices (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

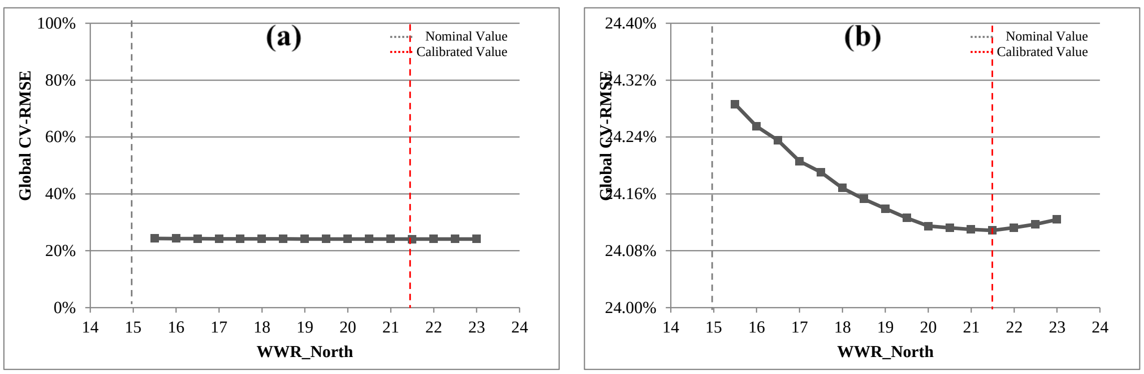


Figure F.17 *Global CV (RMSE) Changes for WWR for North (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

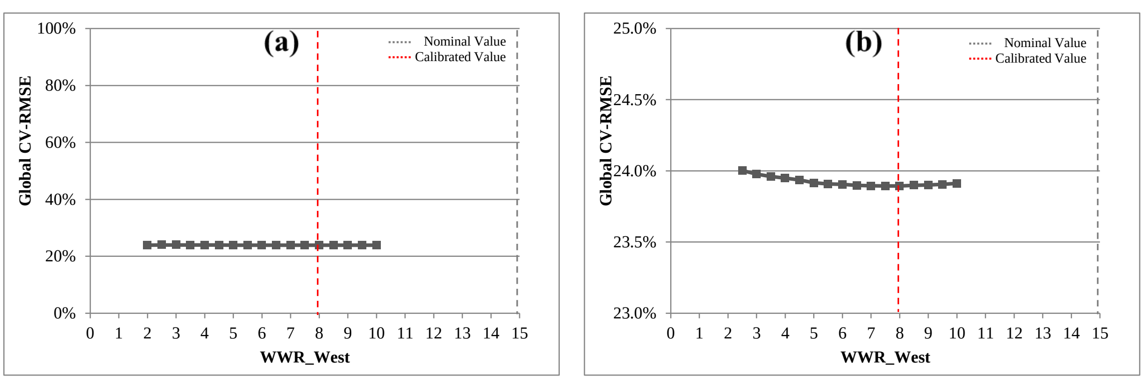


Figure F.18 *Global CV (RMSE) Changes for WWR for West (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

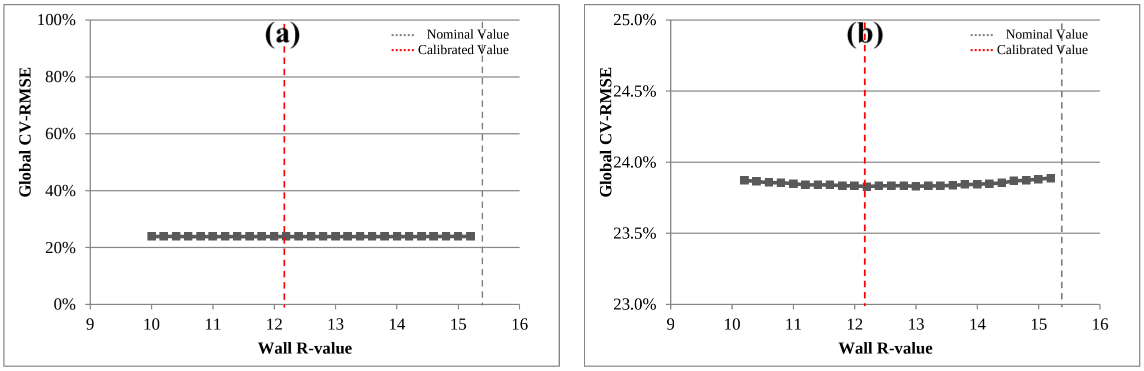


Figure F.19 Global CV (RMSE) Changes for Wall R-value (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

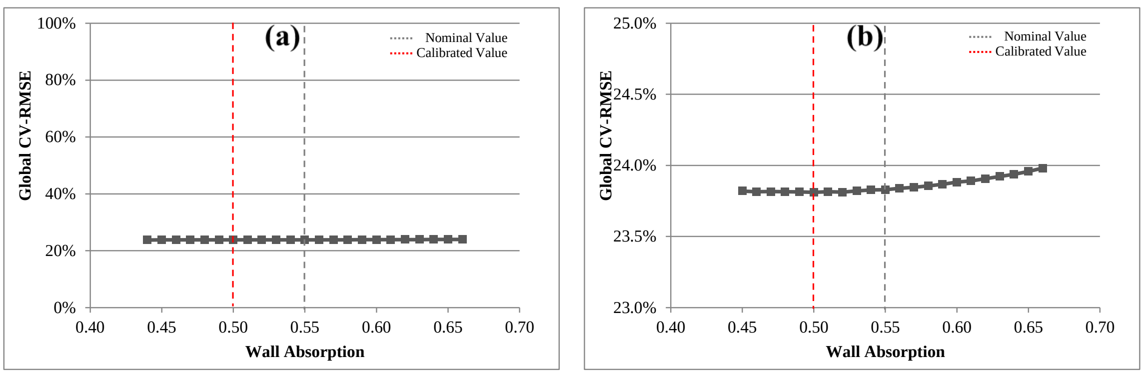


Figure F.20 Global CV (RMSE) Changes for Wall Absorption (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

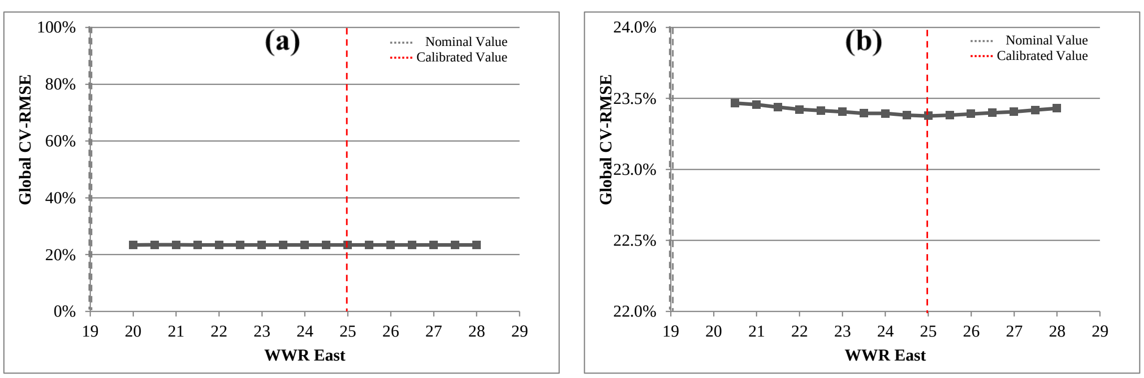


Figure F.21 Global CV (RMSE) Changes for WWR for East (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

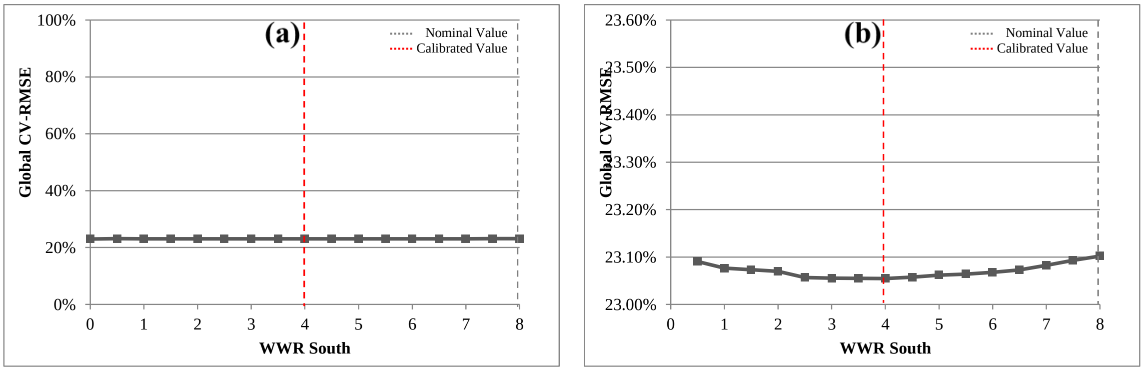


Figure F.22 Global CV (RMSE) Changes for WWR for South (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

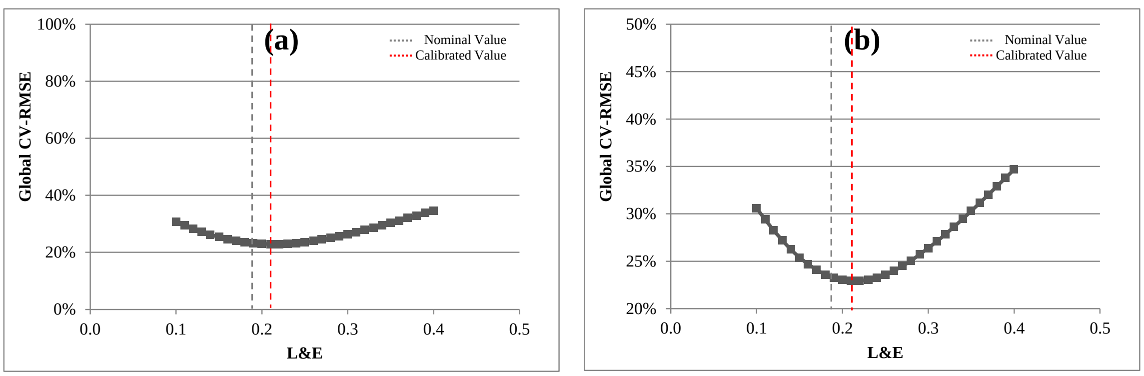


Figure F.23 Global CV (RMSE) Changes for L&E (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

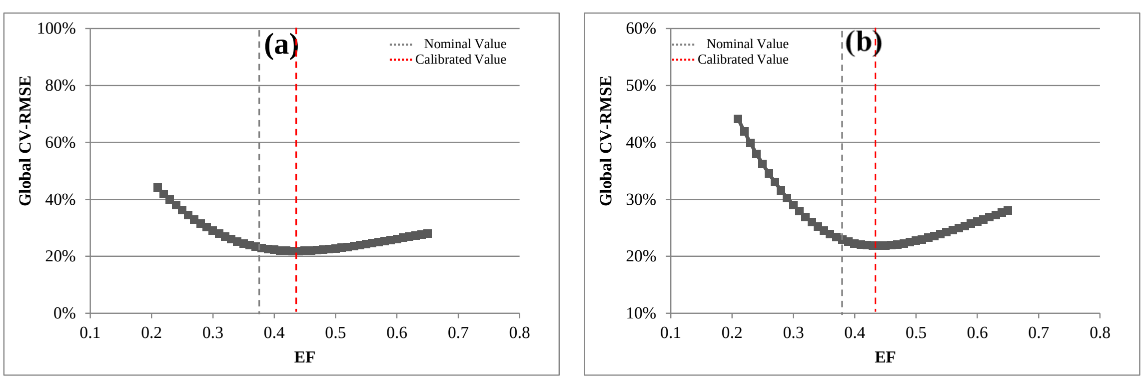


Figure F.24 Global CV (RMSE) Changes for EF (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

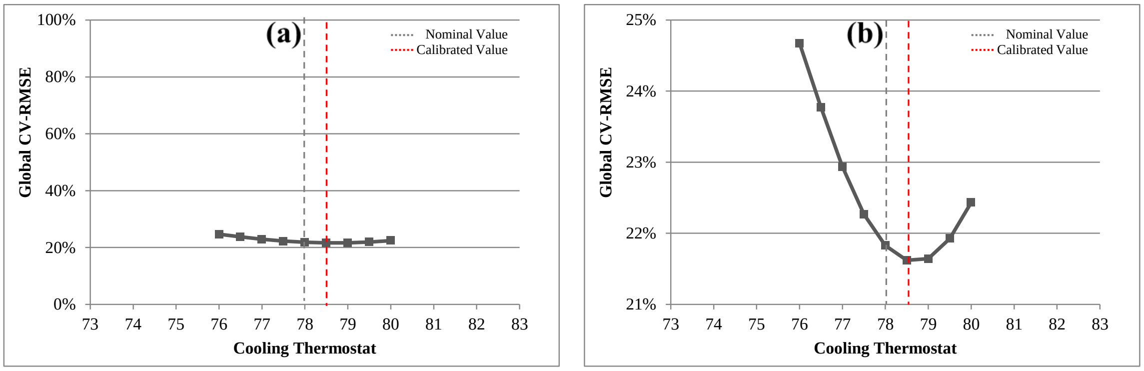


Figure F.25 *Global CV (RMSE) Changes for Cooling Thermostat Setpoint Temperature (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

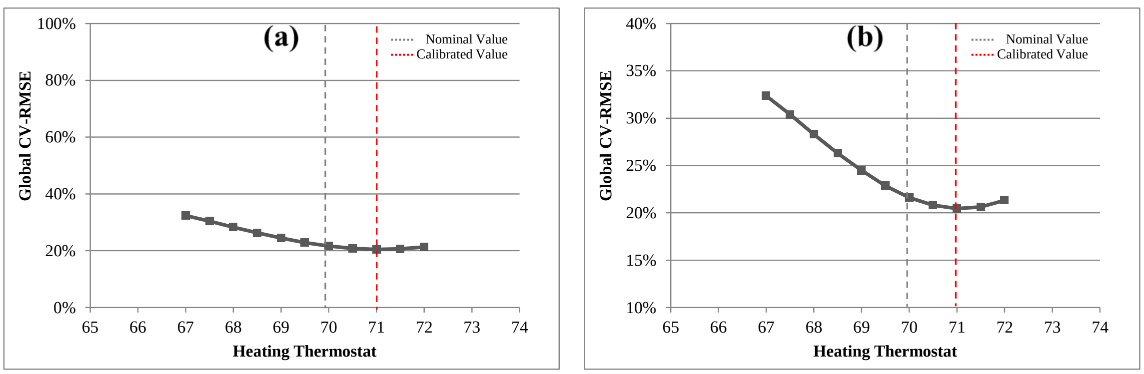


Figure F.26 *Global CV (RMSE) Changes for Heating Thermostat Setpoint Temperature (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

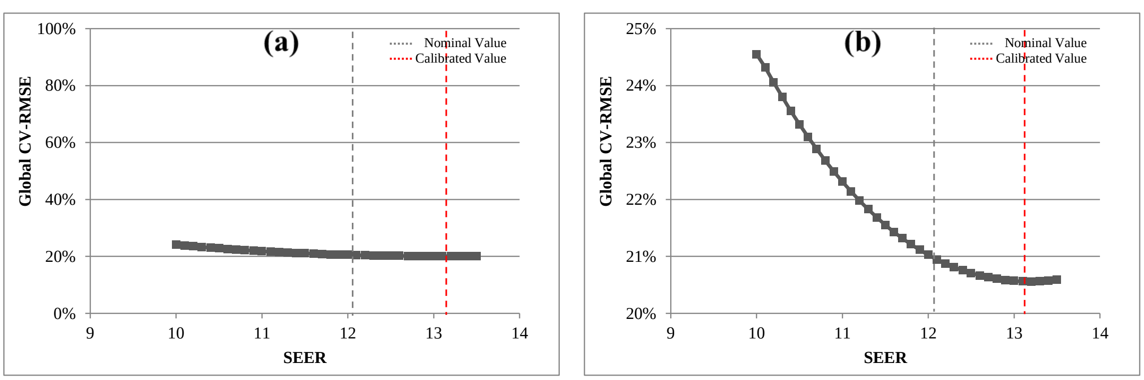


Figure F.27 *Global CV (RMSE) Changes for SEER (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

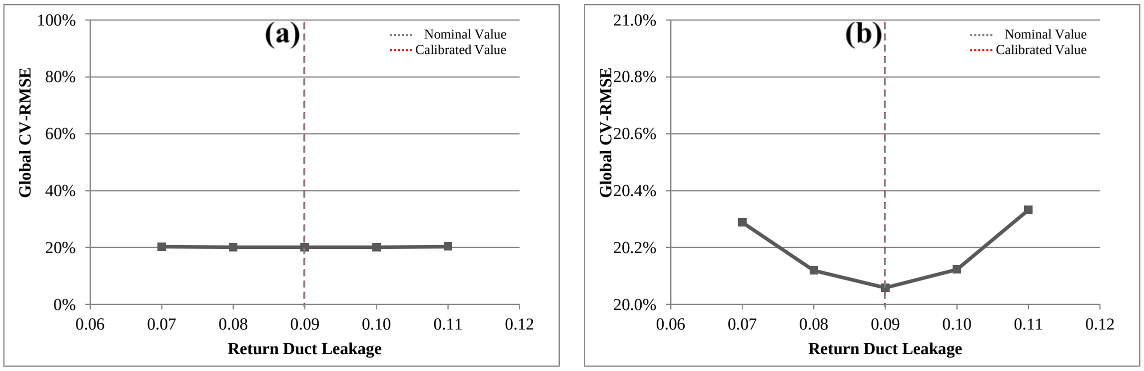


Figure F.28 Global CV (RMSE) Changes for Return Duct Leakage (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

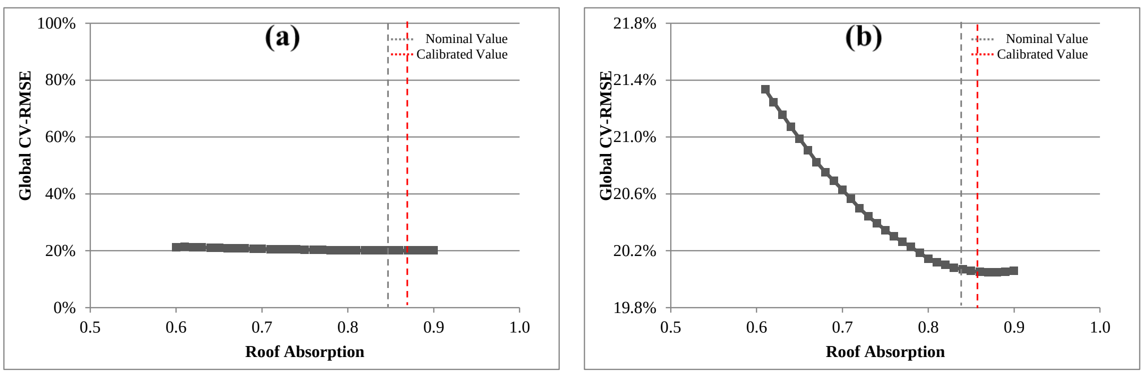


Figure F.29 Global CV (RMSE) Changes for Roof Absorption (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

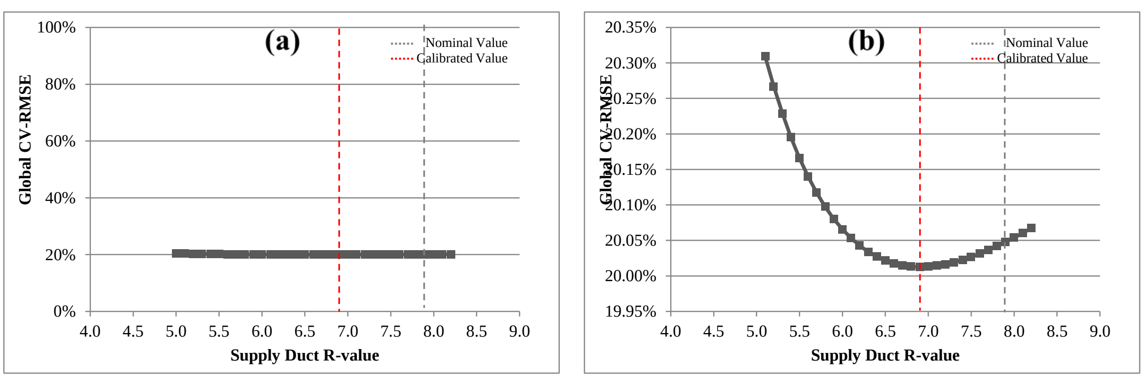


Figure F.30 Global CV (RMSE) Changes for Supply Duct R-value (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

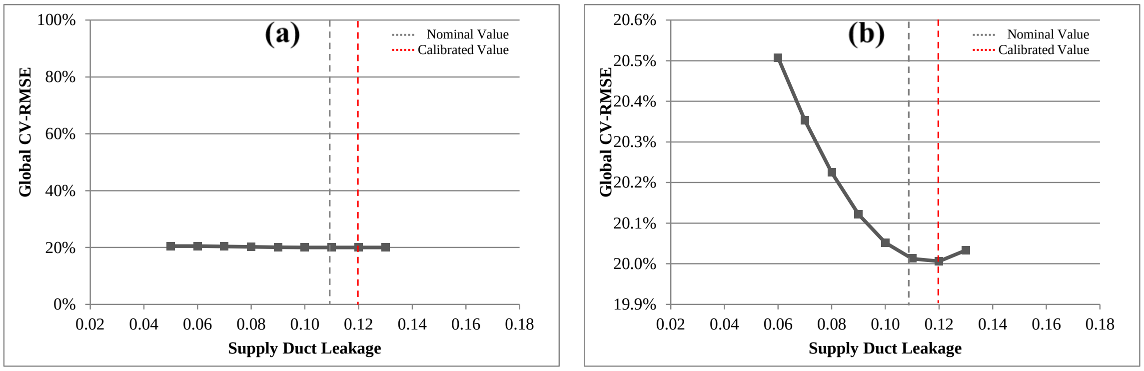


Figure F.31 Global CV (RMSE) Changes for Supply Duct Leakage (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

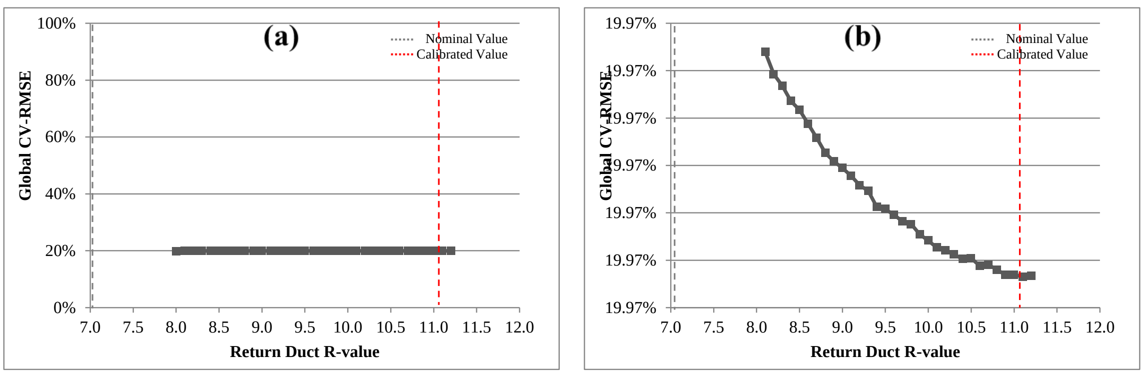


Figure F.32 Global CV (RMSE) Changes for Return Duct R-value (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

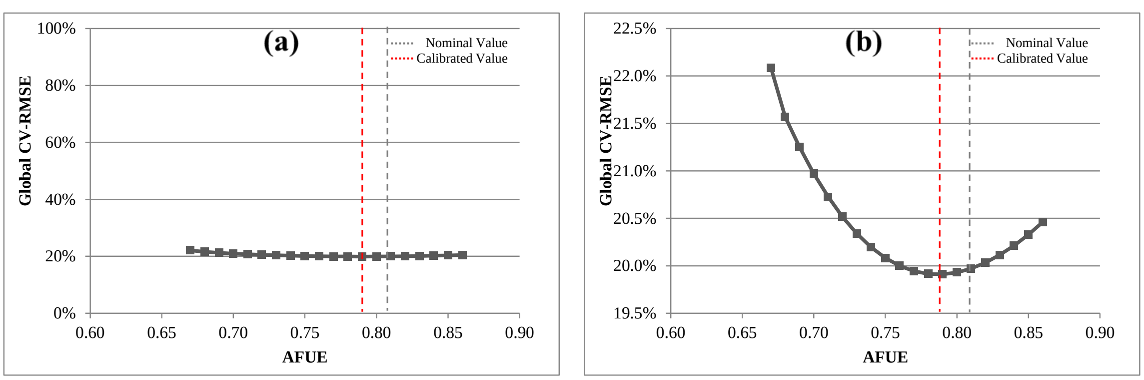


Figure F.33 Global CV (RMSE) Changes for AFUE (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

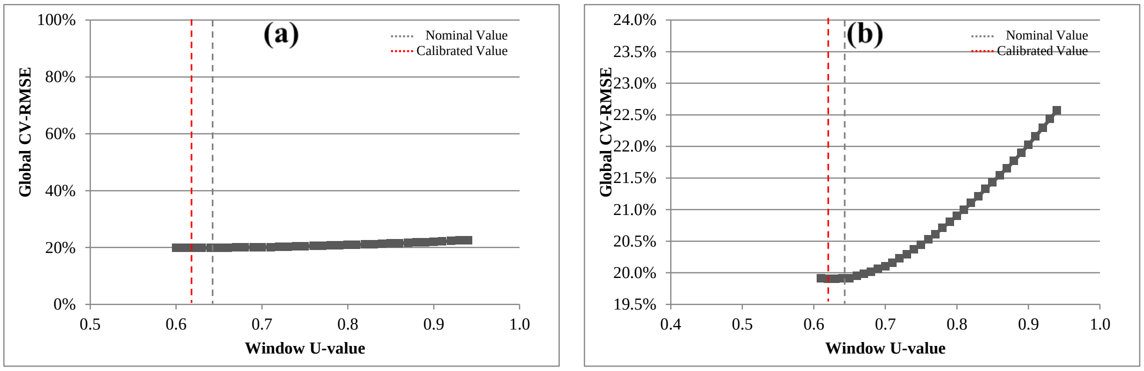


Figure F.34 *Global CV (RMSE) Changes for Window U-value (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

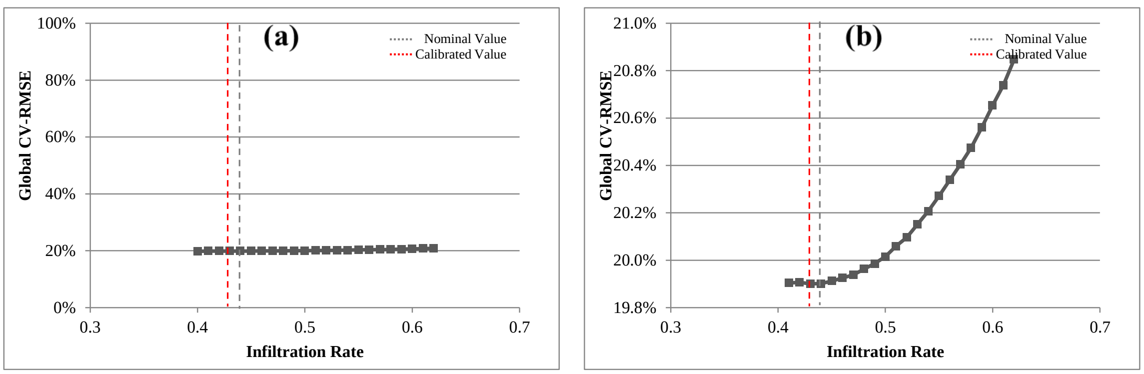


Figure F.35 *Global CV (RMSE) Changes for Infiltration Rate (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

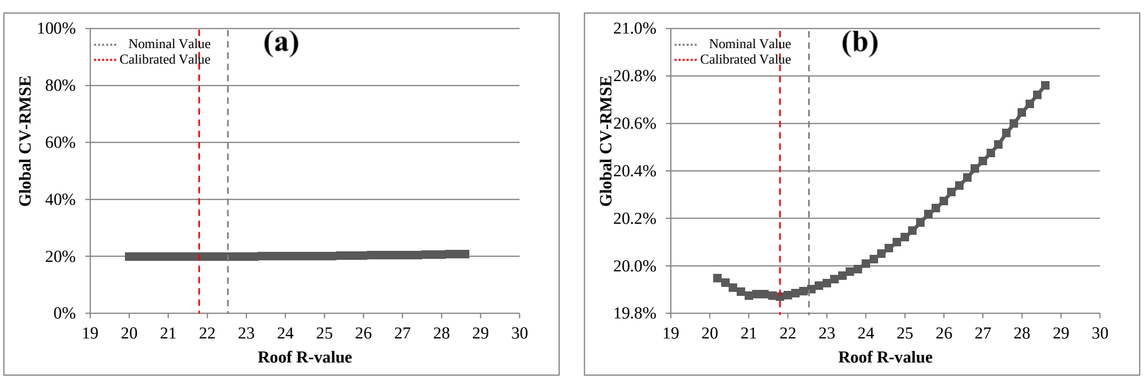


Figure F.36 *Global CV (RMSE) Changes for Roof R-value (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

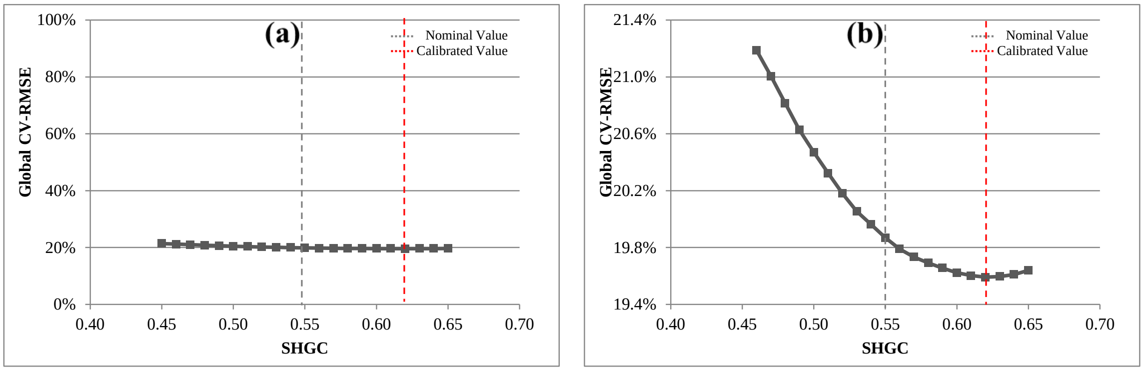


Figure F.37 Global CV (RMSE) Changes for SHGC (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

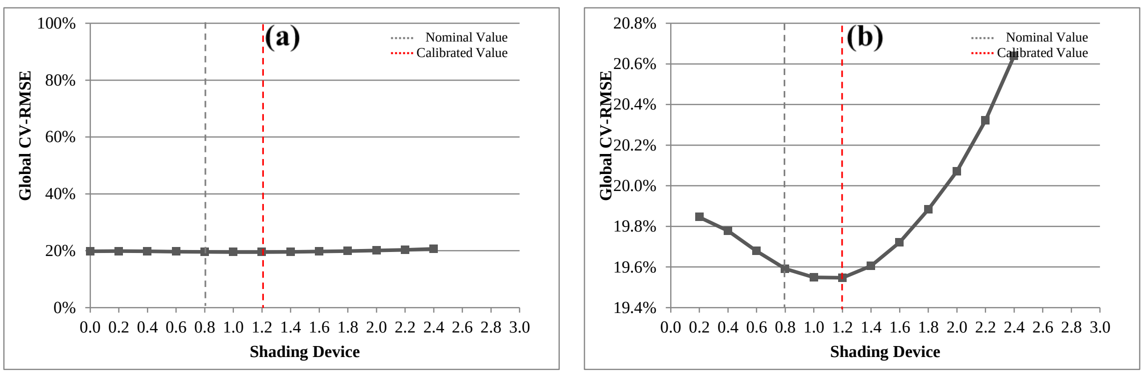


Figure F.38 Global CV (RMSE) Changes for Shading Device (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

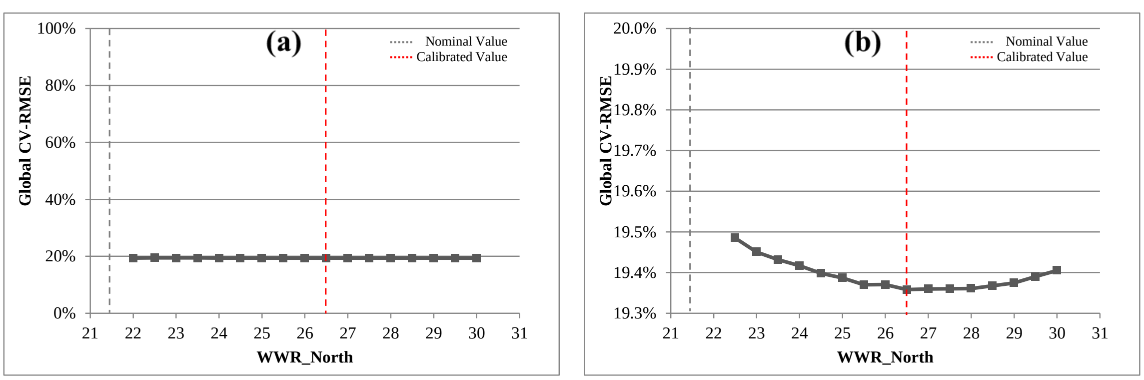


Figure F.39 Global CV (RMSE) Changes for WWR for North (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

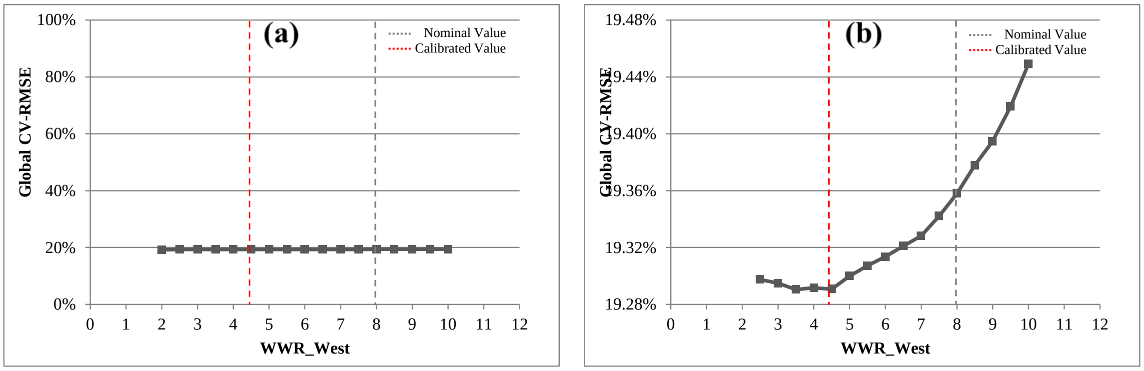


Figure F.40 Global CV (RMSE) Changes for WWR for West (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

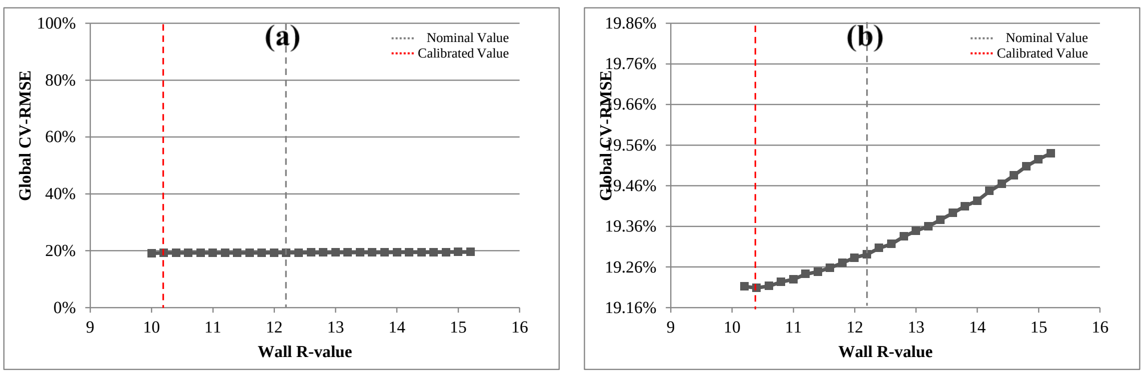


Figure F.41 Global CV (RMSE) Changes for Wall R-value (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

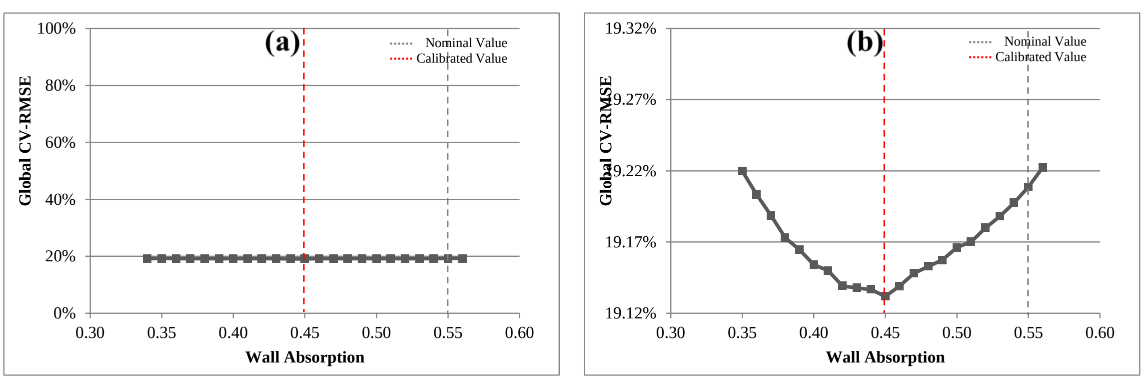


Figure F.42 Global CV (RMSE) Changes for Wall Absorption (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

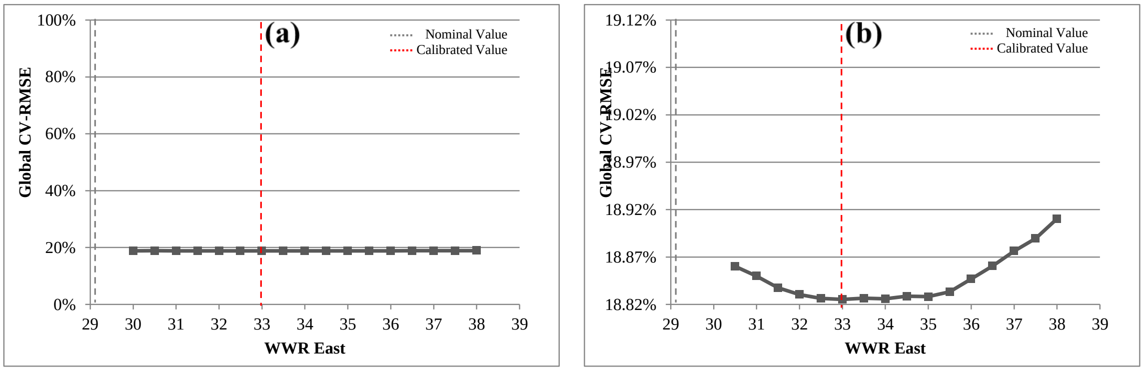


Figure F.43 Global CV (RMSE) Changes for WWR for East (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

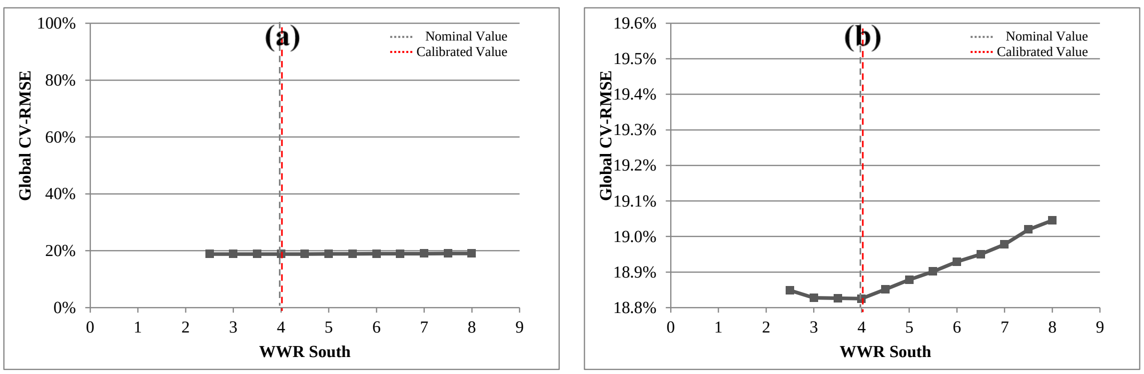


Figure F.44 Global CV (RMSE) Changes for WWR for South (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

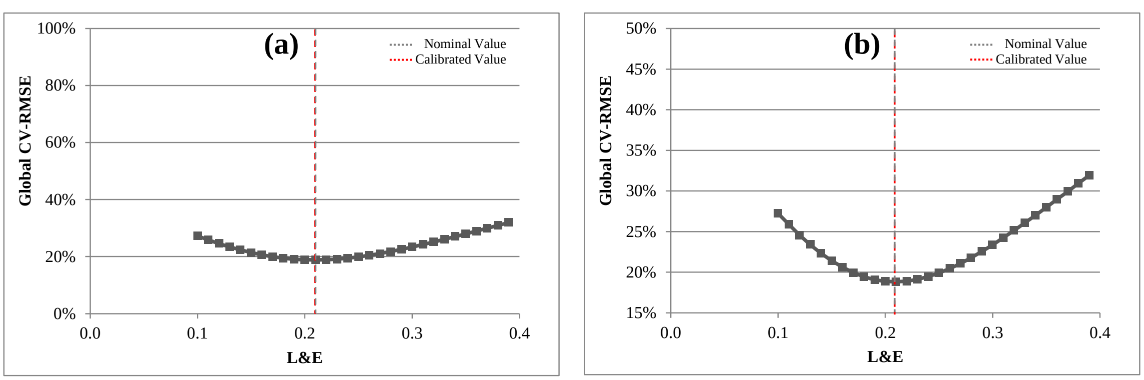


Figure F.45 Global CV (RMSE) Changes for L&E (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

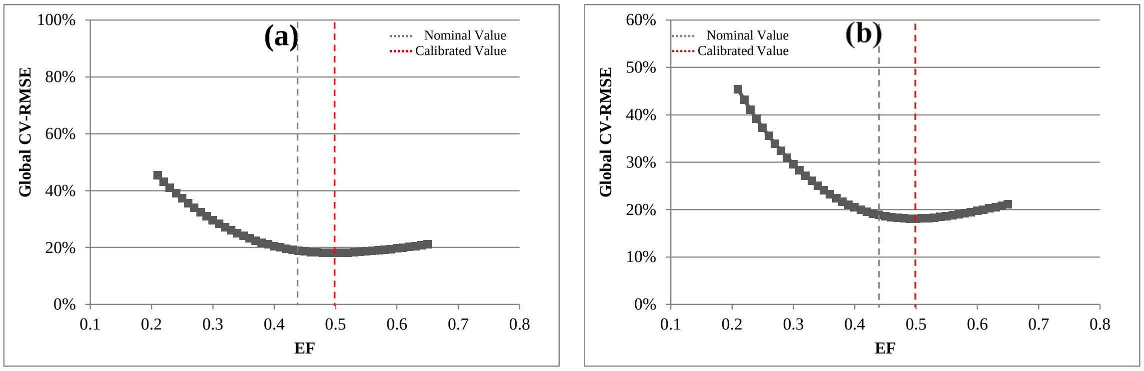


Figure F.46 Global CV (RMSE) Changes for EF (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

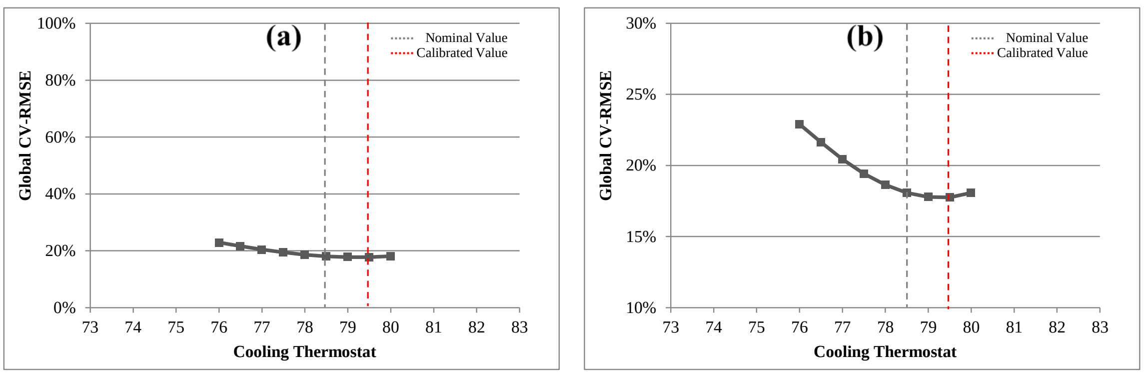


Figure F.47 Global CV (RMSE) Changes for Cooling Thermostat Setpoint Temperature (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

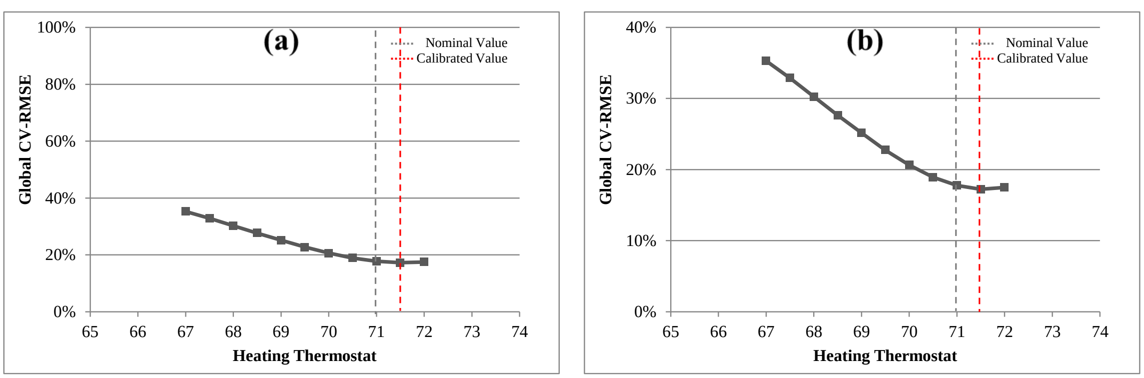


Figure F.48 Global CV (RMSE) Changes for Heating Thermostat Setpoint Temperature (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

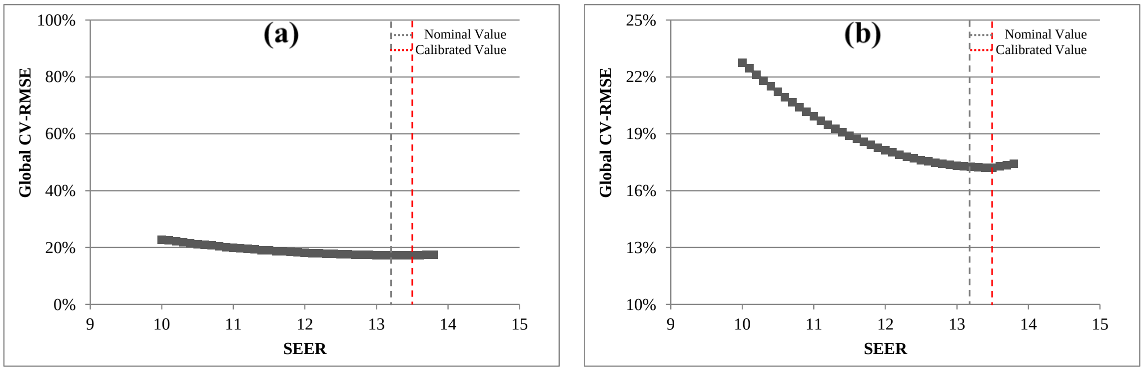


Figure F.49 Global CV (RMSE) Changes for SEER (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

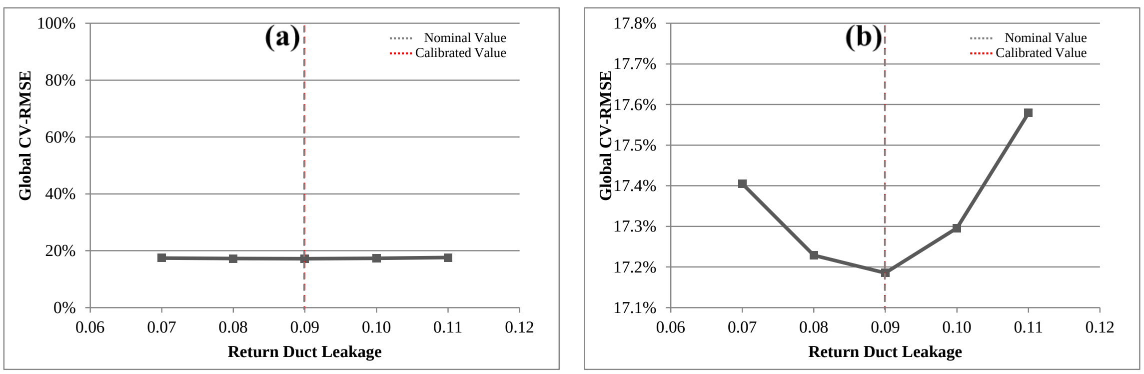


Figure F.50 Global CV (RMSE) Changes for Return Duct Leakage (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

APPENDIX H

CALIBRATION PROCESS FOR EACH PARAMETER OF CASE-STUDY HOUSE #3

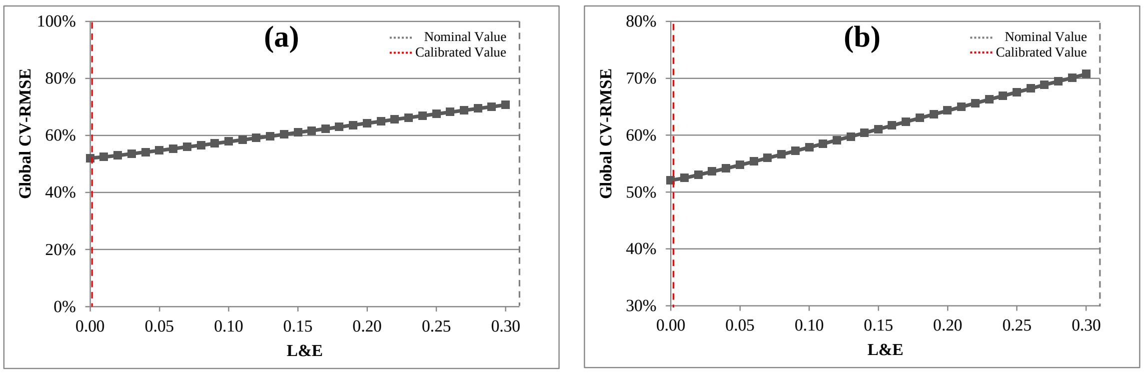


Figure G.1 Global CV (RMSE) Changes for L&E (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

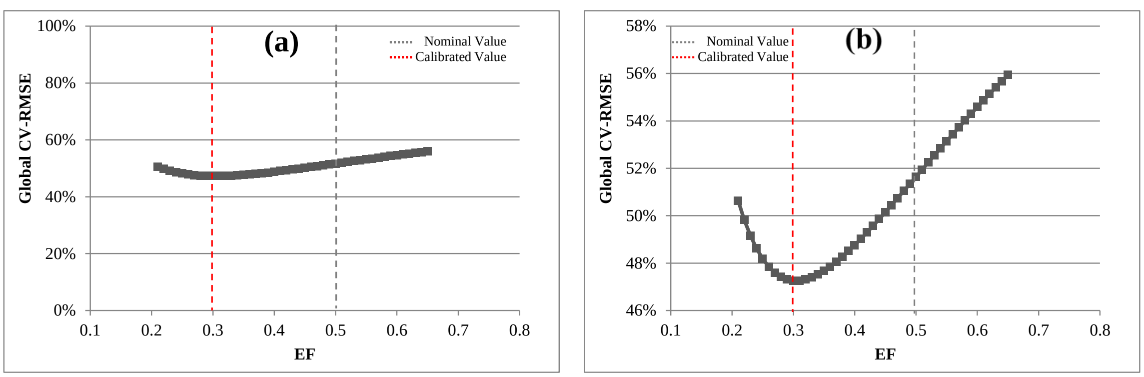


Figure G.2 Global CV (RMSE) Changes for EF (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

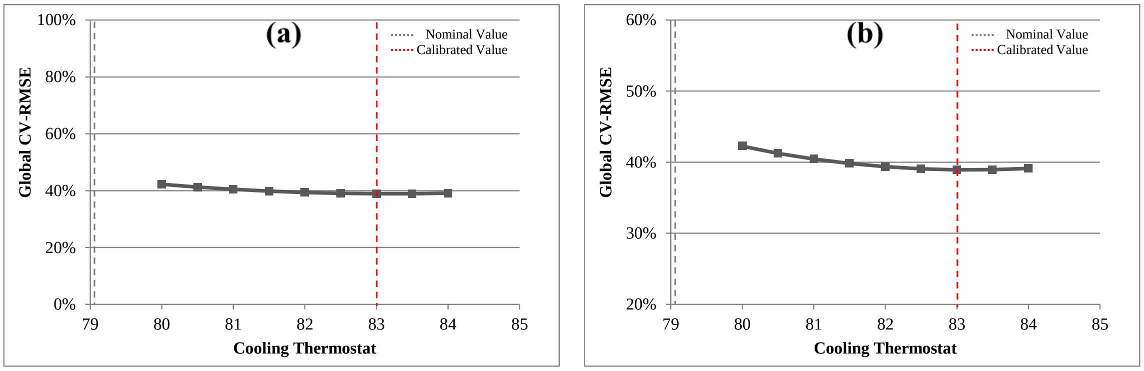


Figure G.3 *Global CV (RMSE) Changes for Cooling Thermostat Setpoint Temperature (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

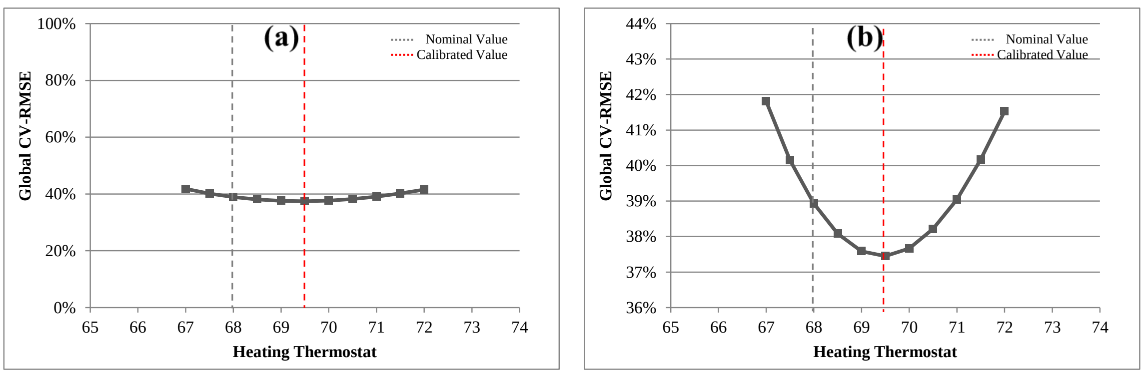


Figure G.4 *Global CV (RMSE) Changes for Heating Thermostat Setpoint Temperature (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

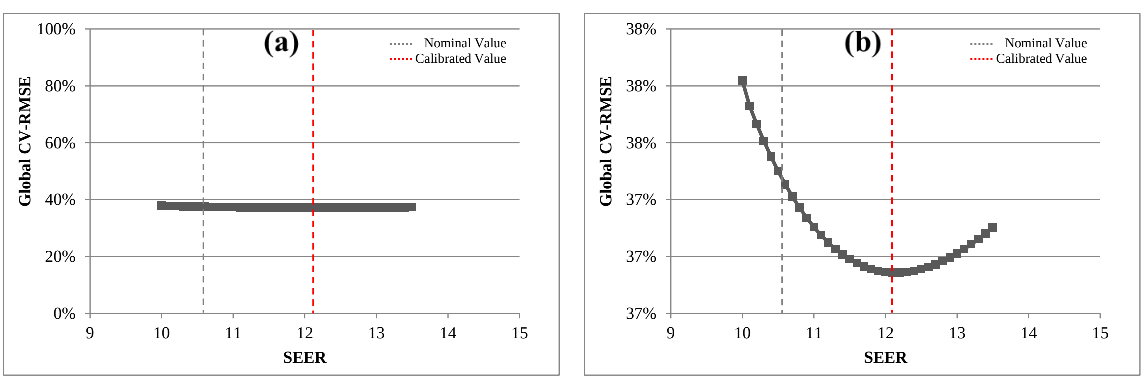


Figure G.5 *Global CV (RMSE) Changes for SEER (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

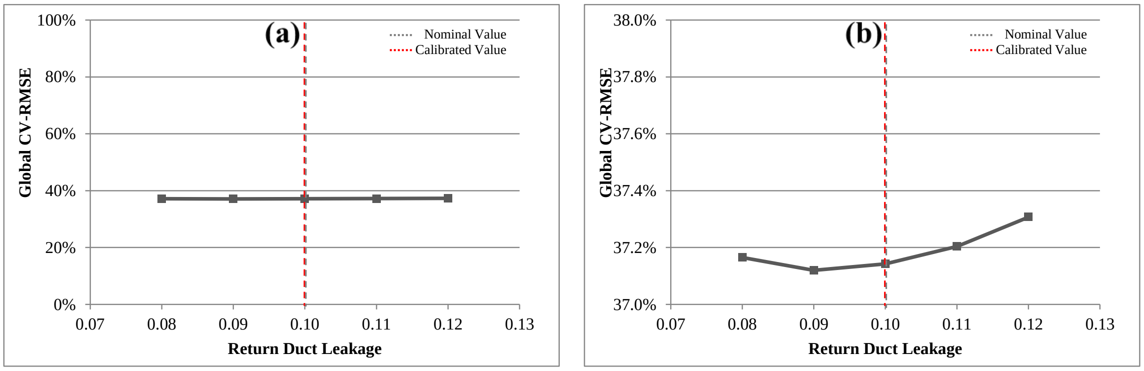


Figure G.6 Global CV (RMSE) Changes for Return Duct Leakage (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

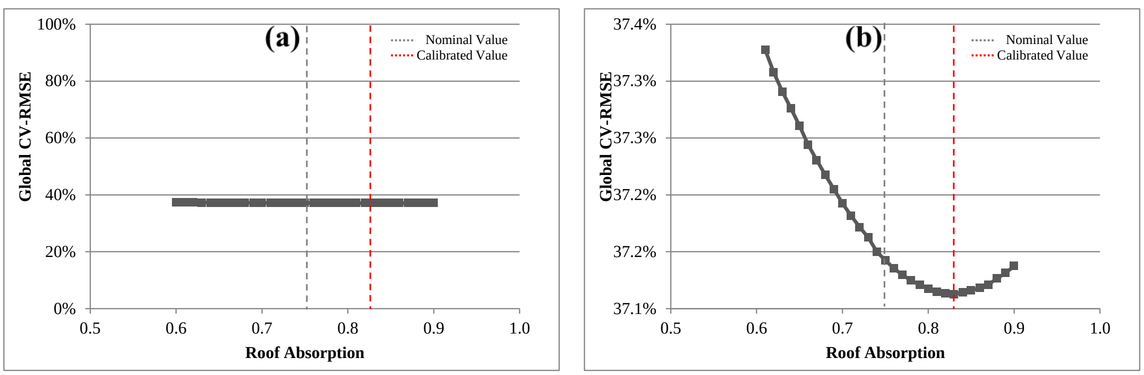


Figure G.7 Global CV (RMSE) Changes for Roof Absorption (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

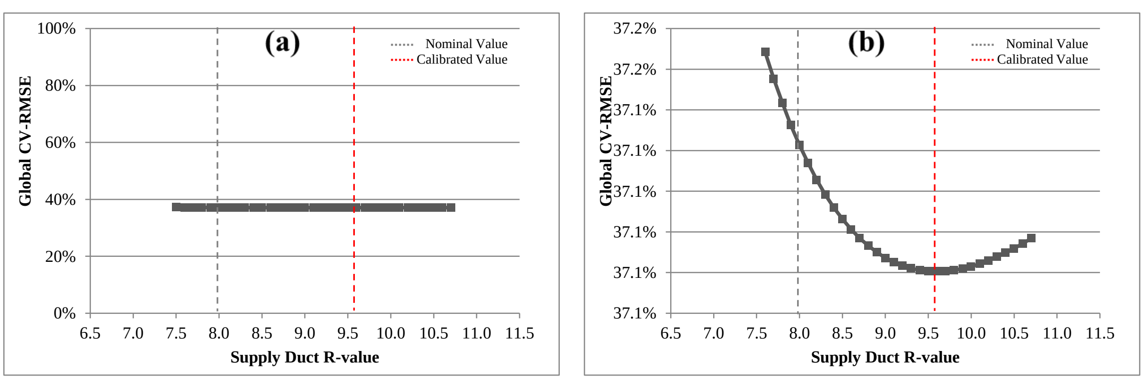


Figure G.8 Global CV (RMSE) Changes for Supply Duct R-value (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

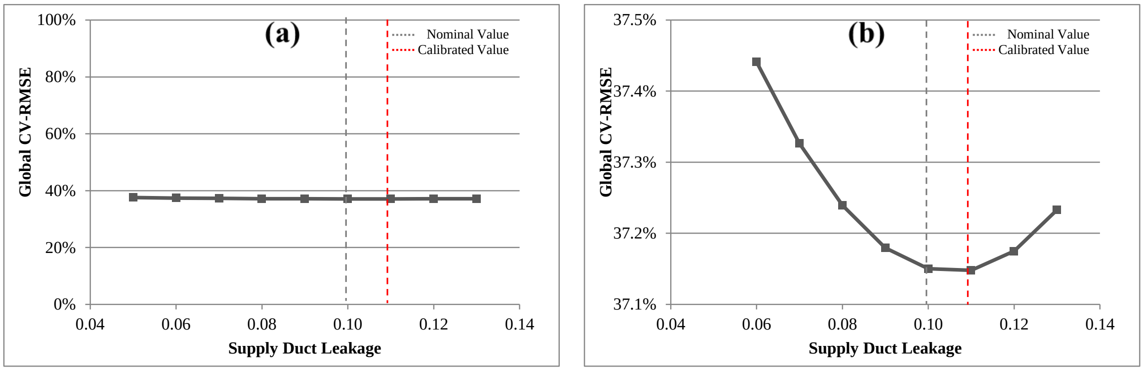


Figure G.9 *Global CV (RMSE) Changes for Supply Duct Leakage (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

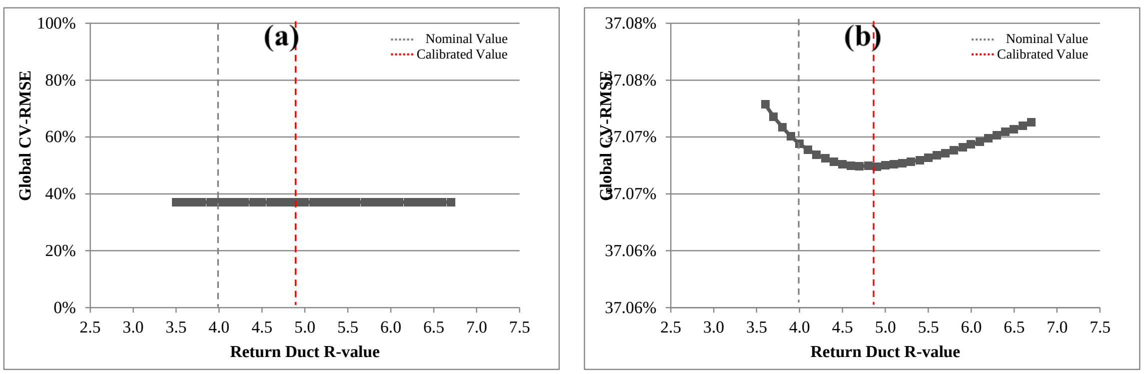


Figure G.10 *Global CV (RMSE) Changes for Return Duct R-value (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

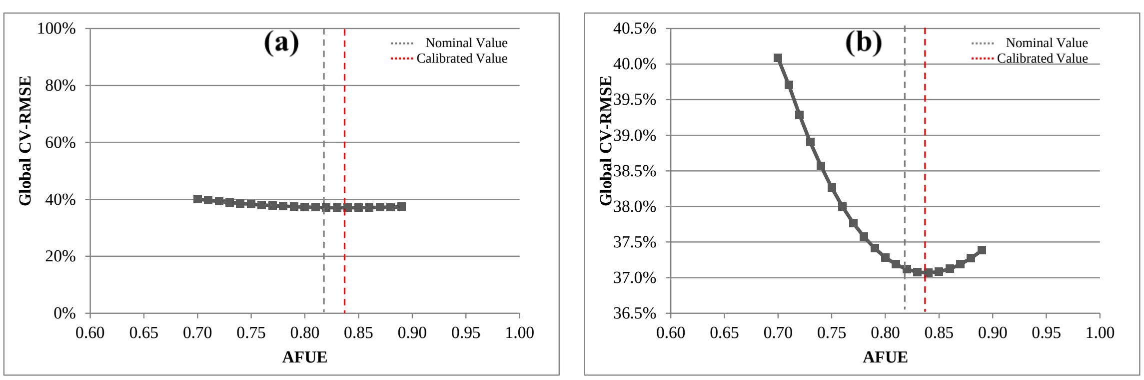


Figure G.11 *Global CV (RMSE) Changes for AFUE (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

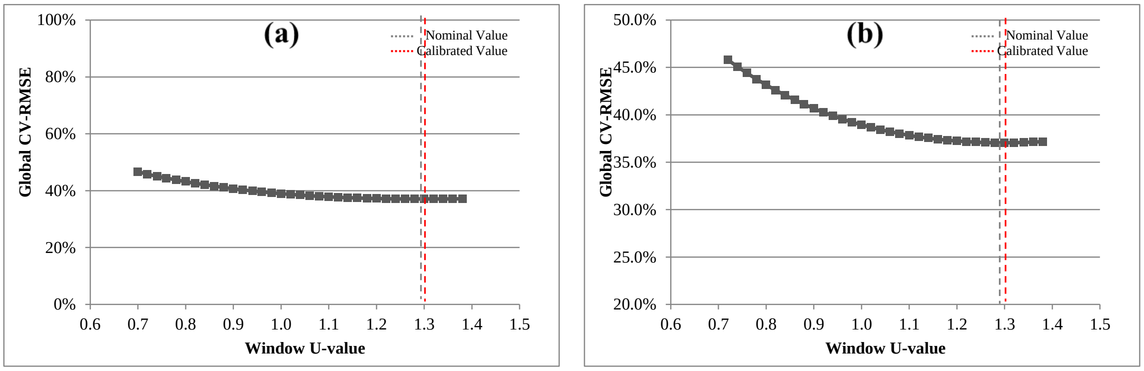


Figure G.12 Global CV (RMSE) Changes for Window U-value (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

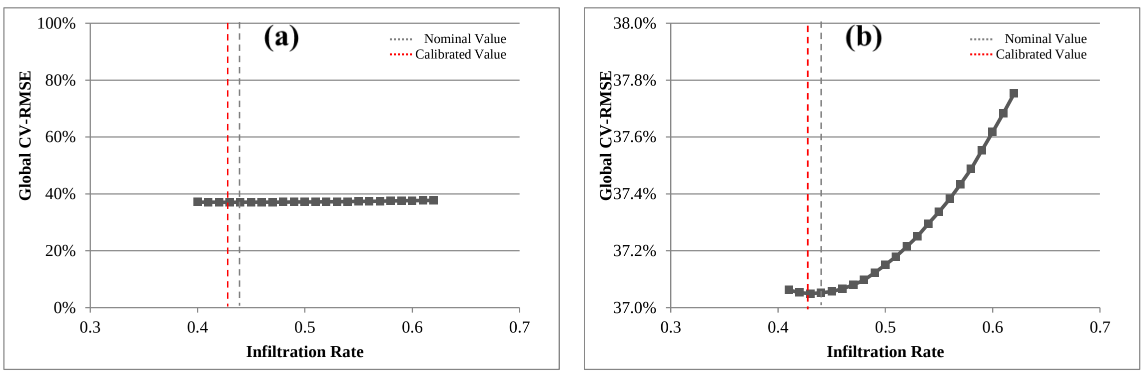


Figure G.13 Global CV (RMSE) Changes for Infiltration Rate (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

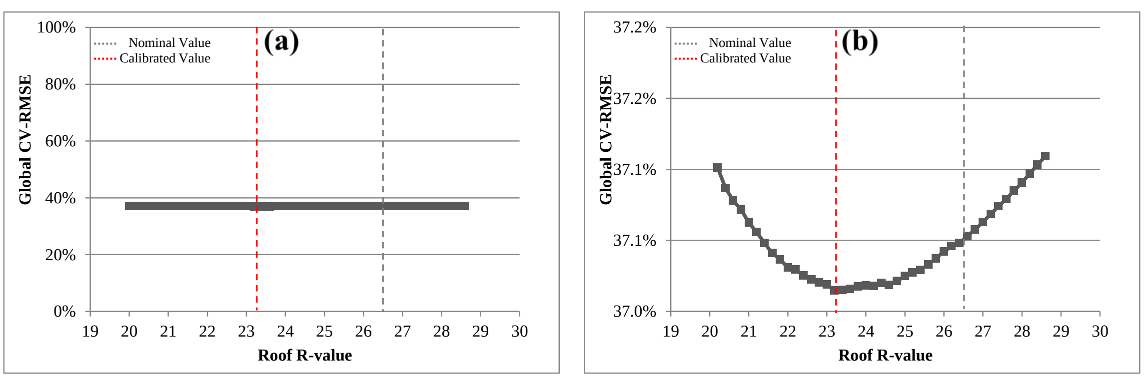


Figure G.14 Global CV (RMSE) Changes for Roof R-value (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

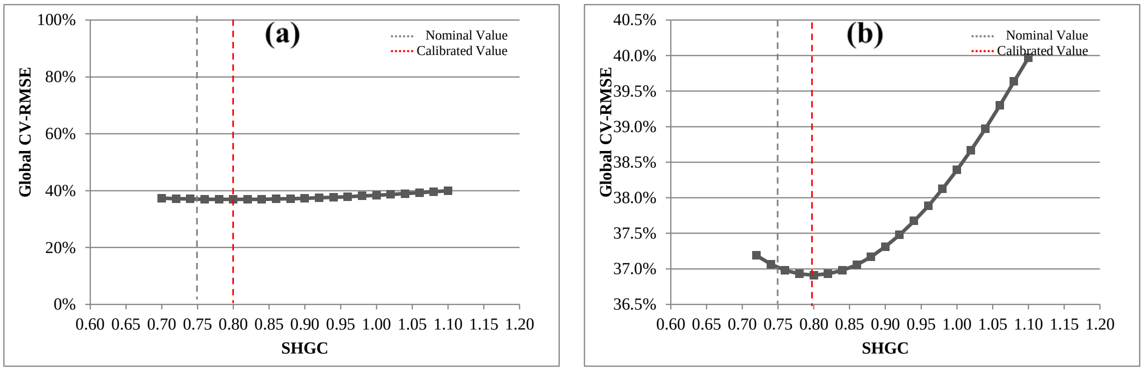


Figure G.15 Global CV (RMSE) Changes for SHGC (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

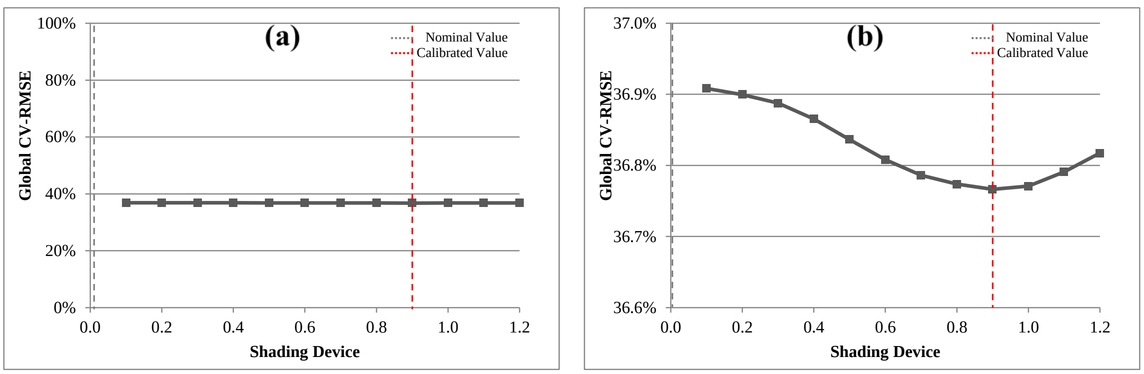


Figure G.16 Global CV (RMSE) Changes for Shading Device (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

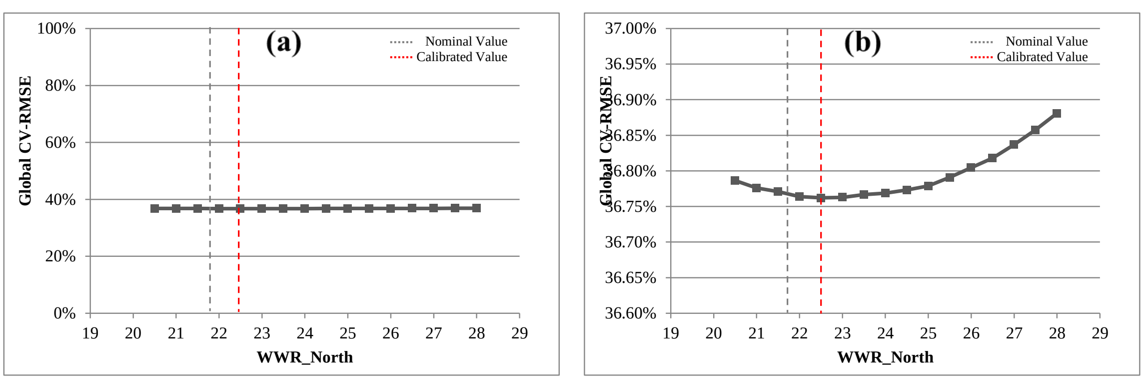


Figure G.17 Global CV (RMSE) Changes for WWR for North (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

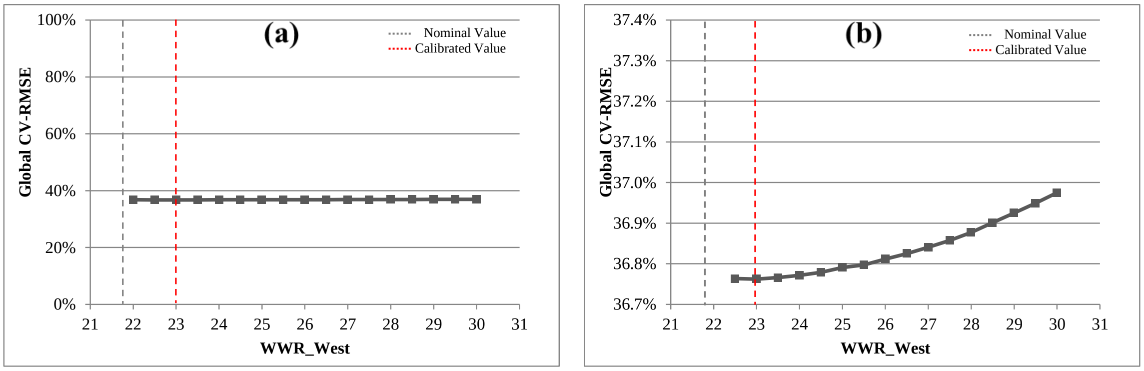


Figure G.18 Global CV (RMSE) Changes for WWR for West (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

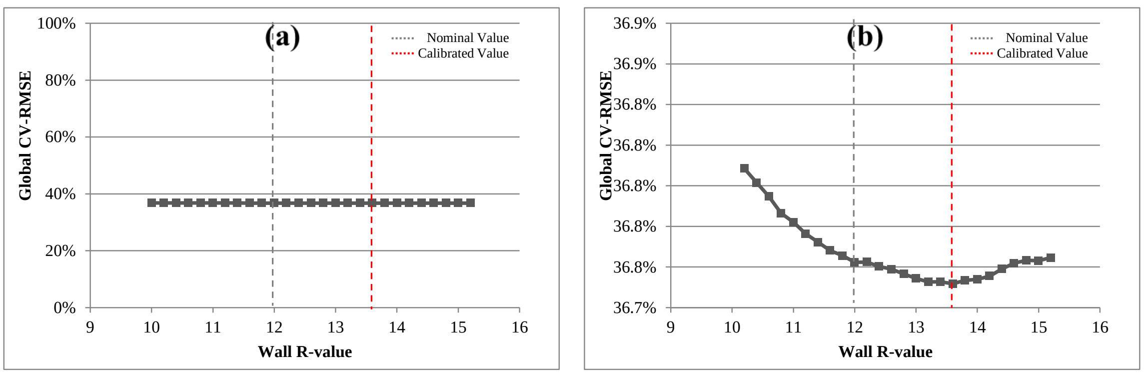


Figure G.19 Global CV (RMSE) Changes for Wall R-value (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

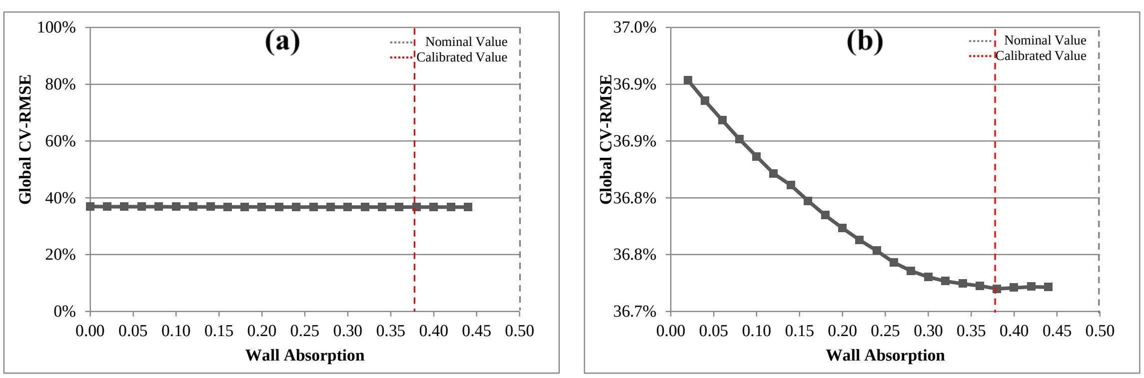


Figure G.20 Global CV (RMSE) Changes for Wall Absorption (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

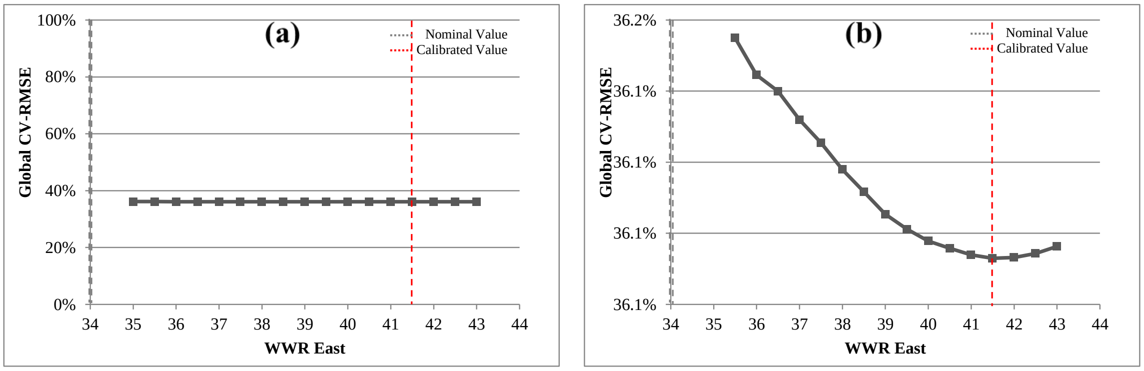


Figure G.21 Global CV (RMSE) Changes for WWR for East (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

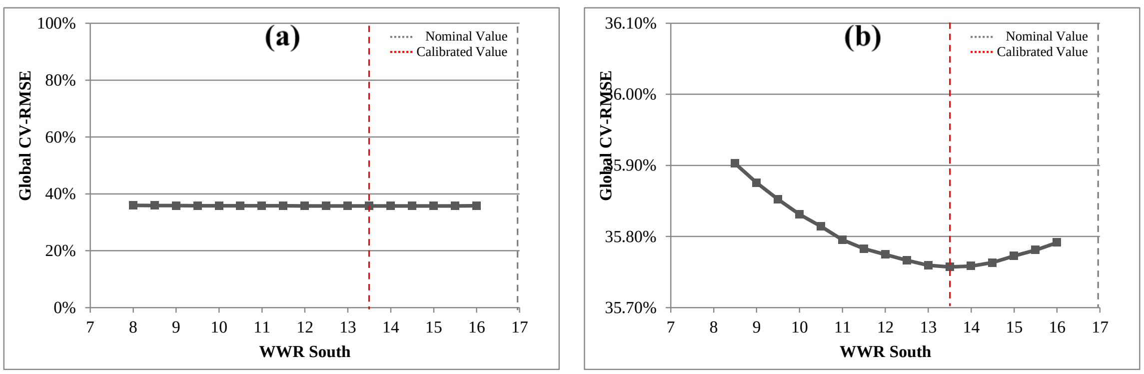


Figure G.22 Global CV (RMSE) Changes for WWR for South (1st Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

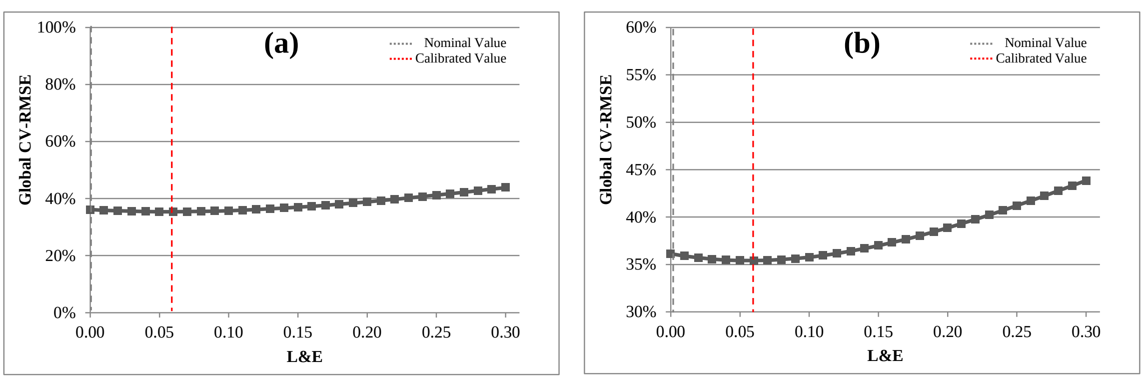


Figure G.23 Global CV (RMSE) Changes for L&E (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

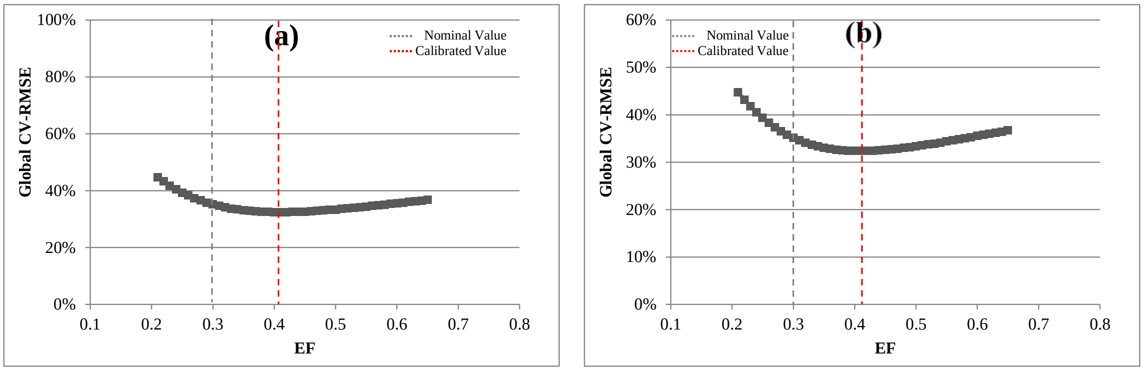


Figure G.24 *Global CV (RMSE) Changes for EF (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

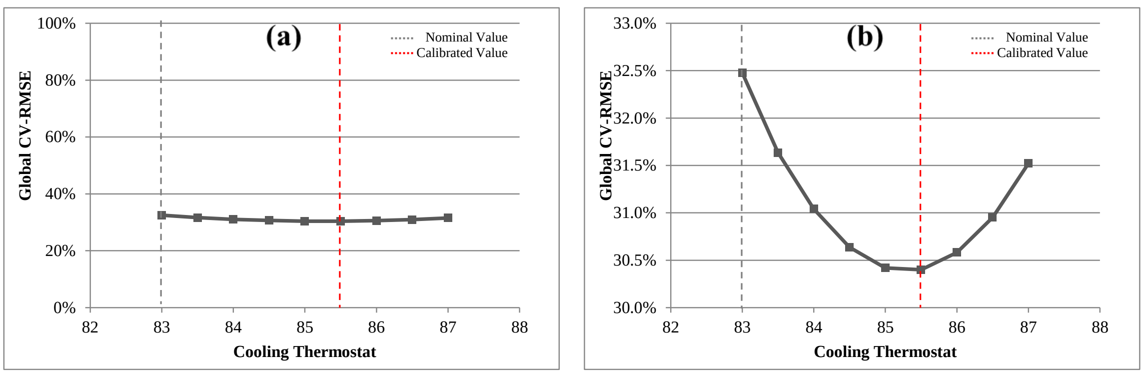


Figure G.25 *Global CV (RMSE) Changes for Cooling Thermostat Temperature (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

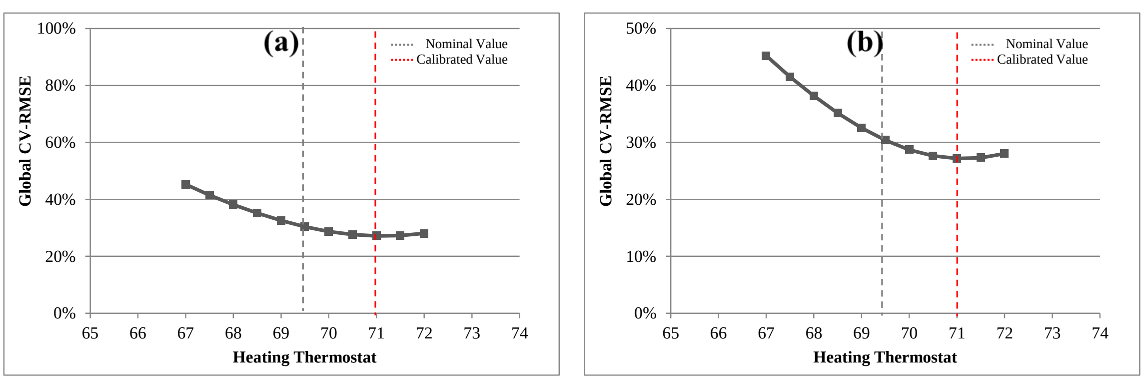


Figure G.26 *Global CV (RMSE) Changes for Heating Thermostat Setpoint Temperature (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

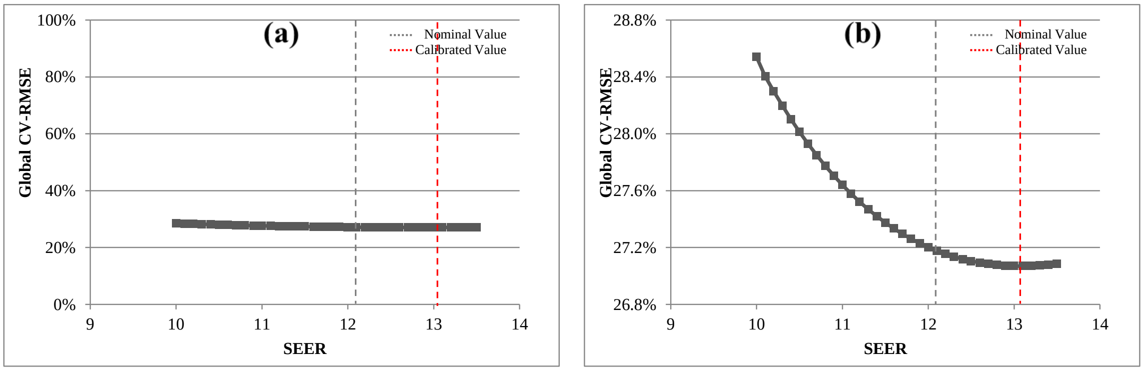


Figure G.27 *Global CV (RMSE) Changes for SEER (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

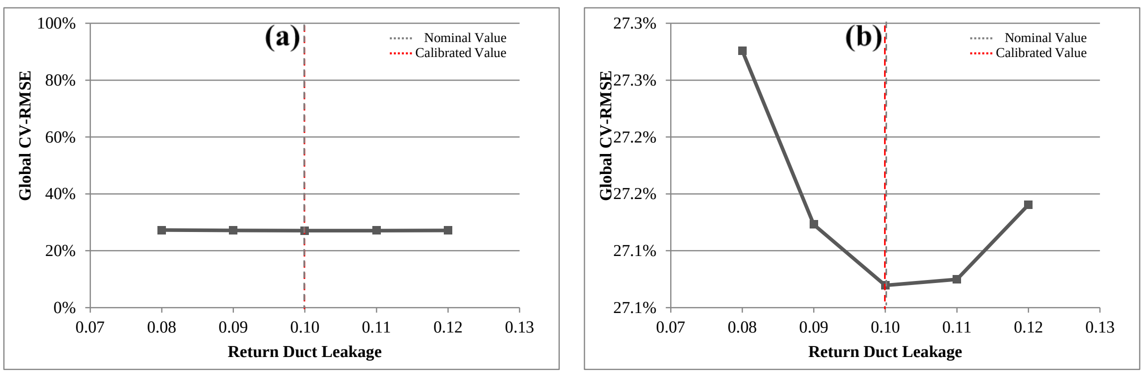


Figure G.28 *Global CV (RMSE) Changes for Return Duct Leakage (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

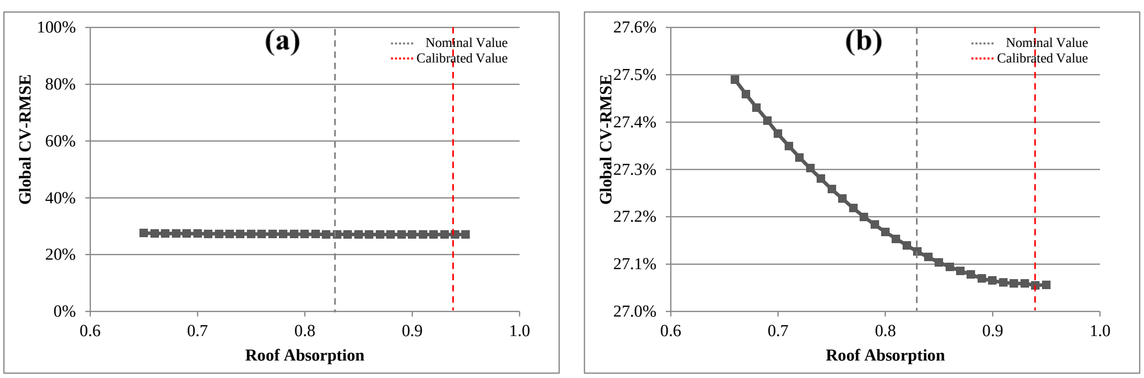


Figure G.29 *Global CV (RMSE) Changes for Roof Absorption (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

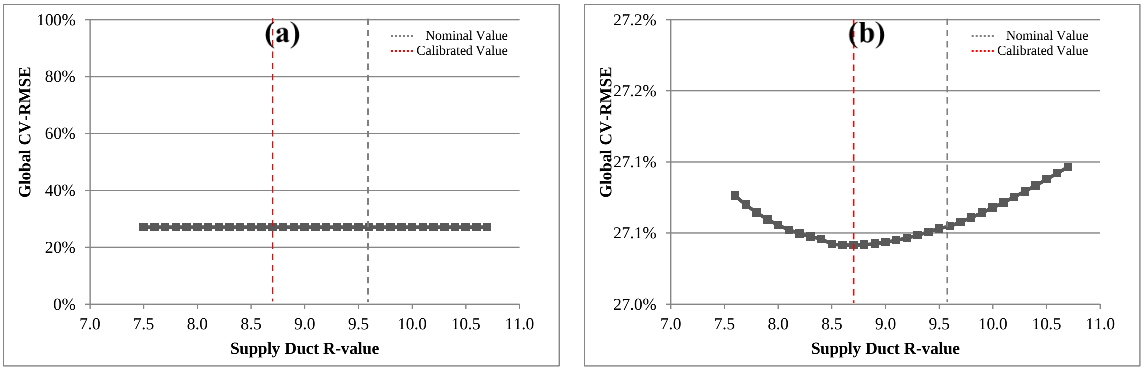


Figure G.30 Global CV (RMSE) Changes for Supply Duct R-value (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

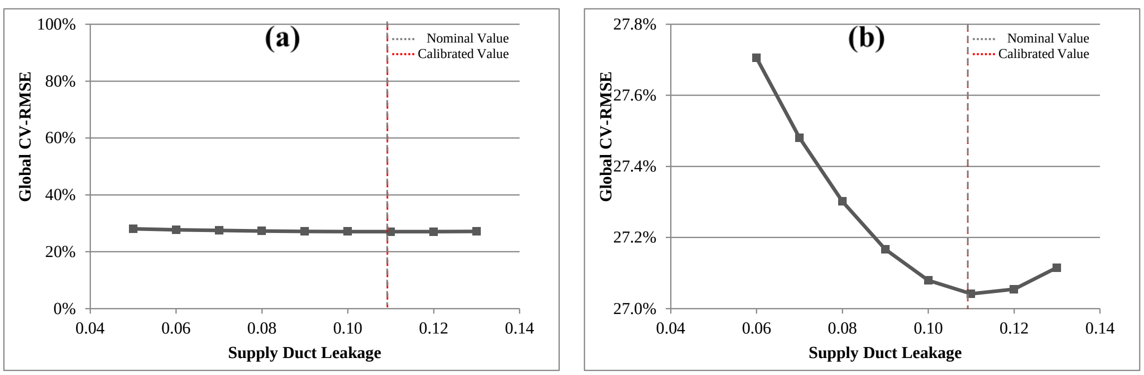


Figure G.31 Global CV (RMSE) Changes for Supply Duct Leakage (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

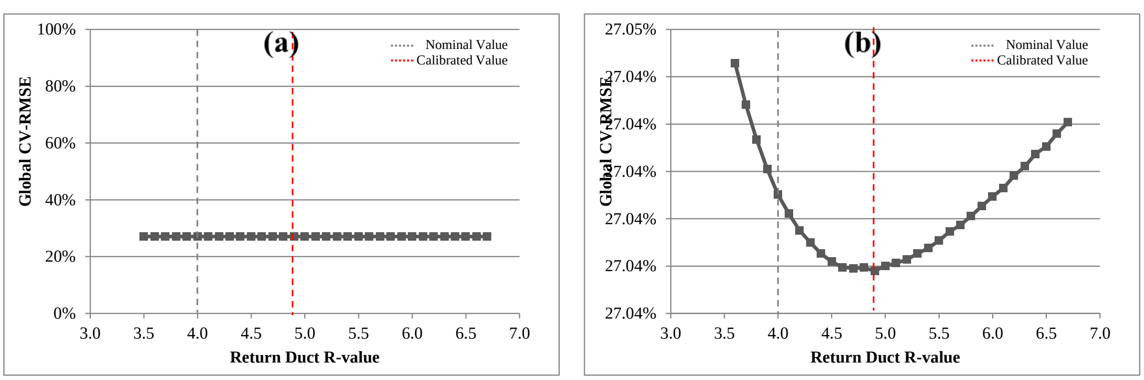


Figure G.32 Global CV (RMSE) Changes for Return Duct R-value (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

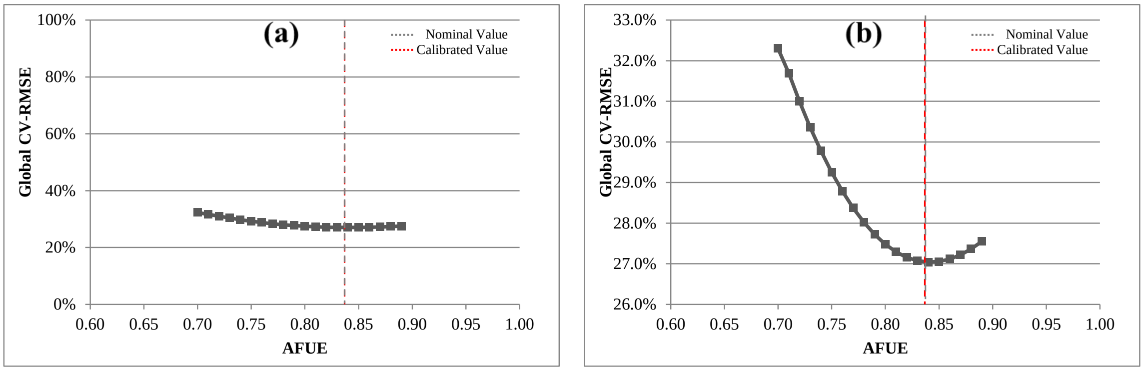


Figure G.33 *Global CV (RMSE) Changes for AFUE (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

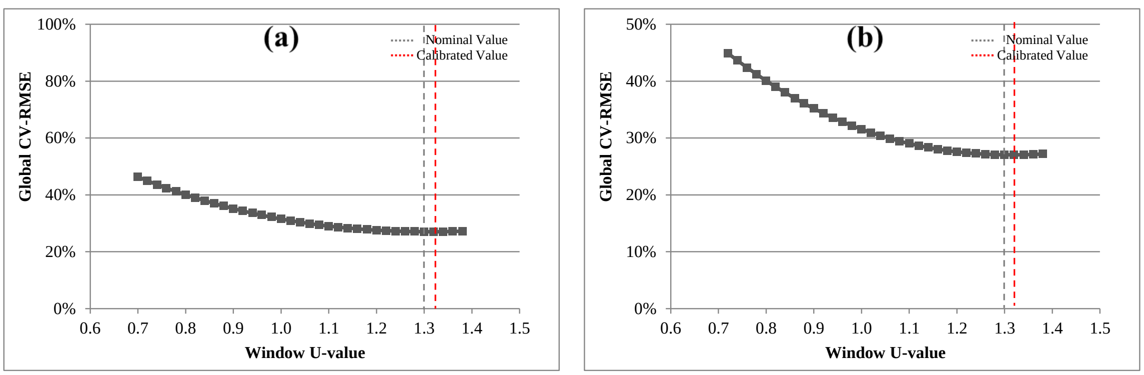


Figure G.34 *Global CV (RMSE) Changes for Window U-value (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

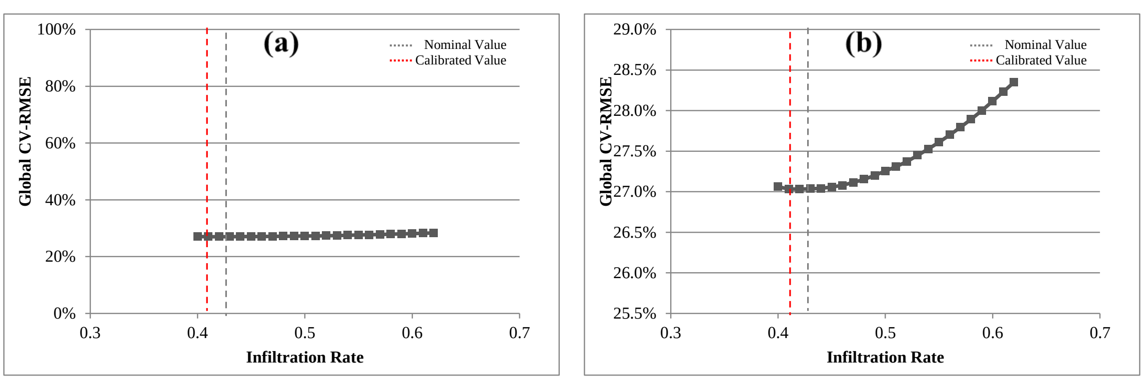


Figure G.35 *Global CV (RMSE) Changes for Infiltration Rate (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

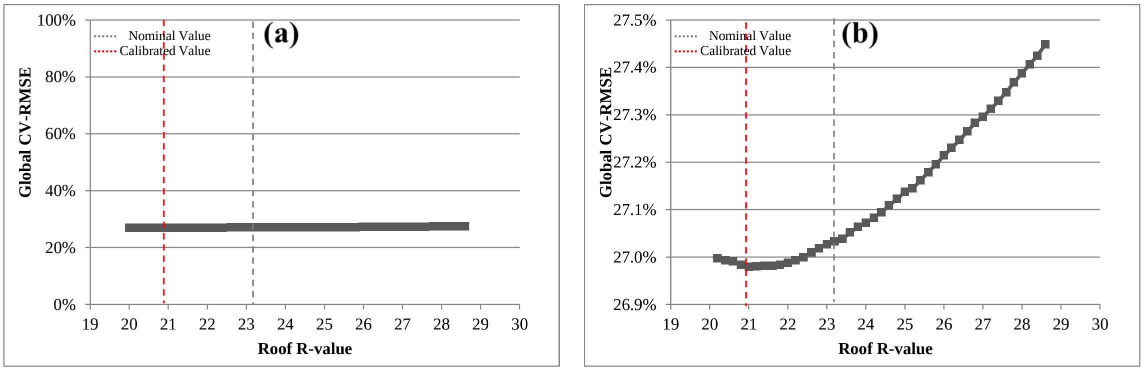


Figure G.36 Global CV (RMSE) Changes for Roof R-value (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

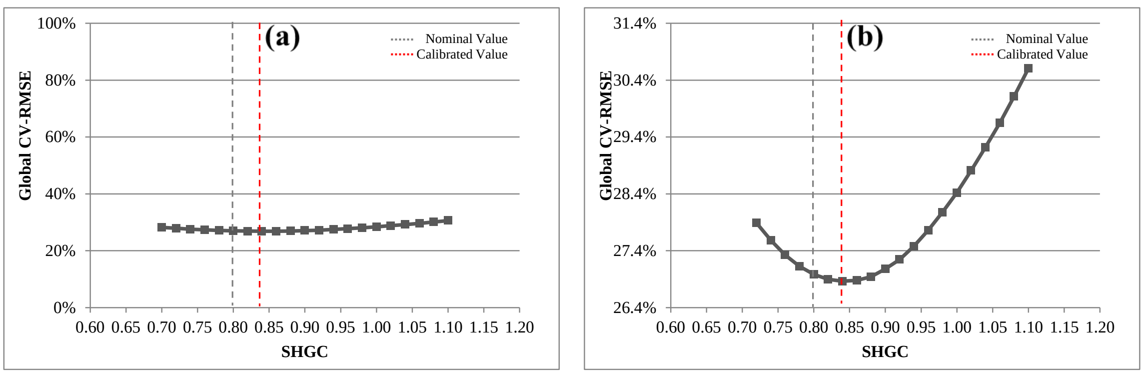


Figure G.37 Global CV (RMSE) Changes for SHGC (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

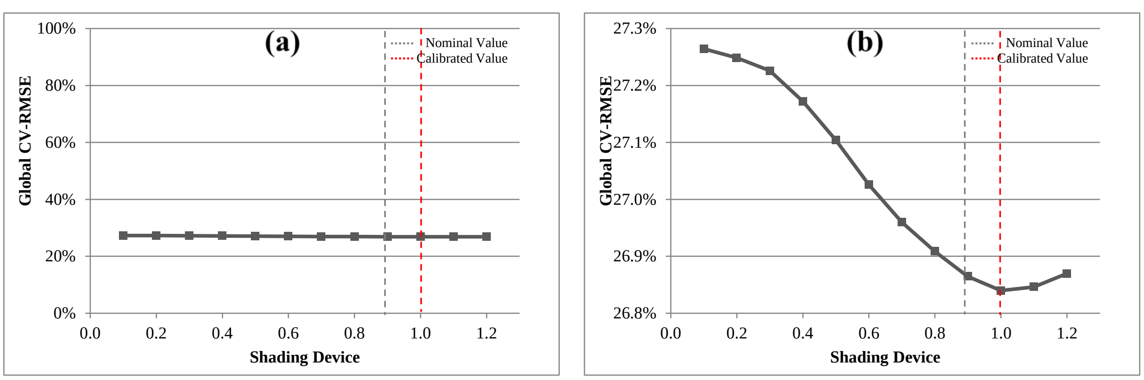


Figure G.38 Global CV (RMSE) Changes for Shding Device (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

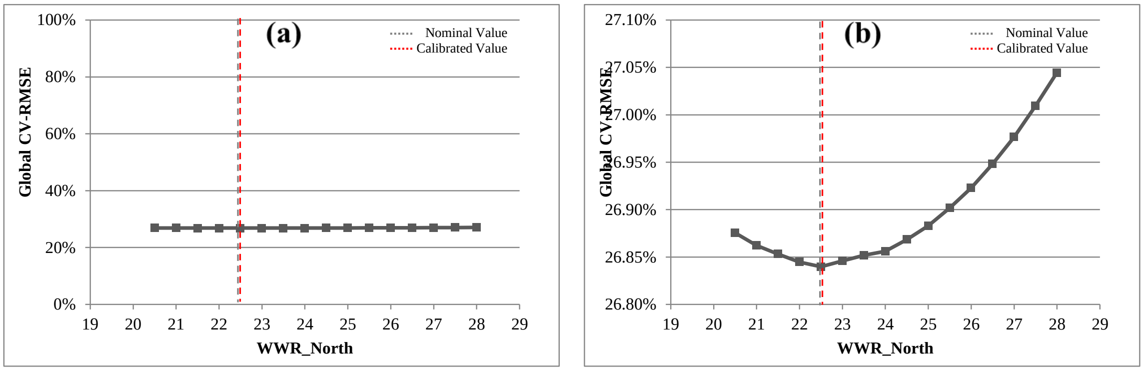


Figure G.39 *Global CV (RMSE) Changes for WWR for North (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

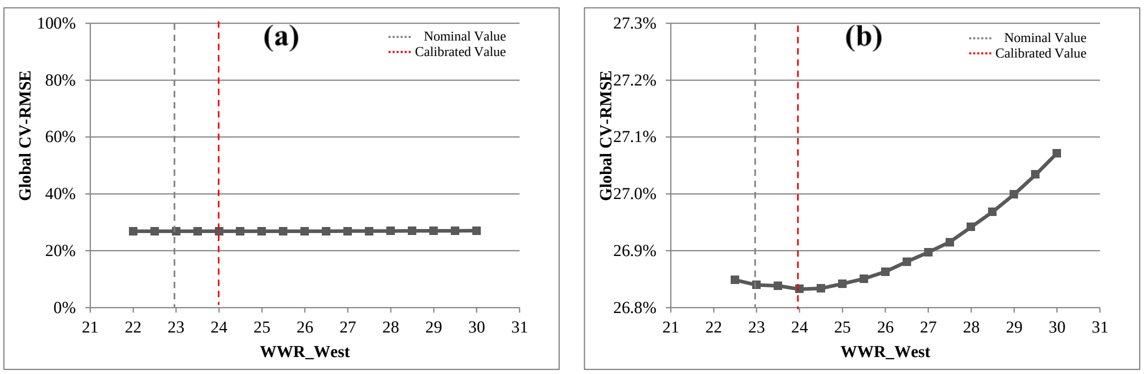


Figure G.40 *Global CV (RMSE) Changes for WWR for West (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

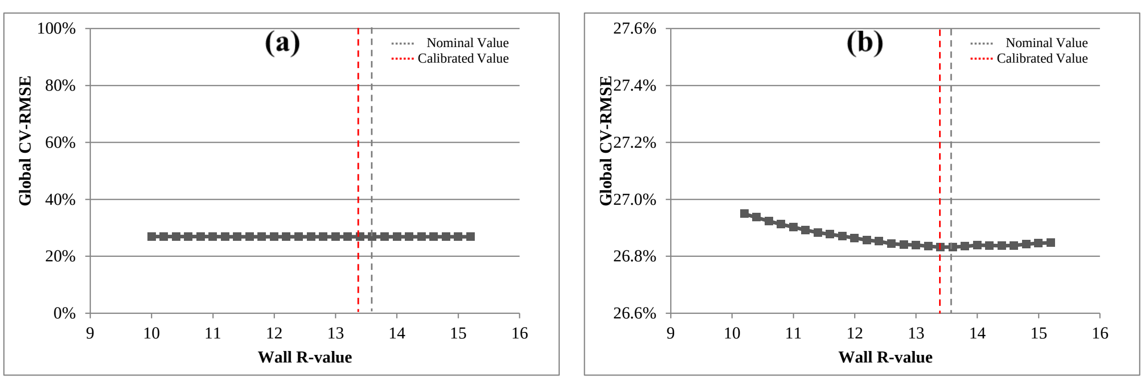


Figure G.41 *Global CV (RMSE) Changes for Wall R-value (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

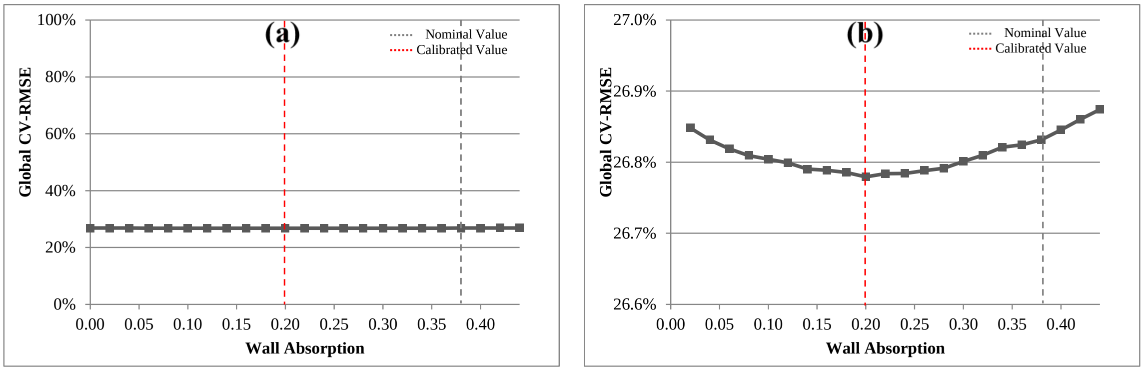


Figure G.42 Global CV (RMSE) Changes for Wall Absorption (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

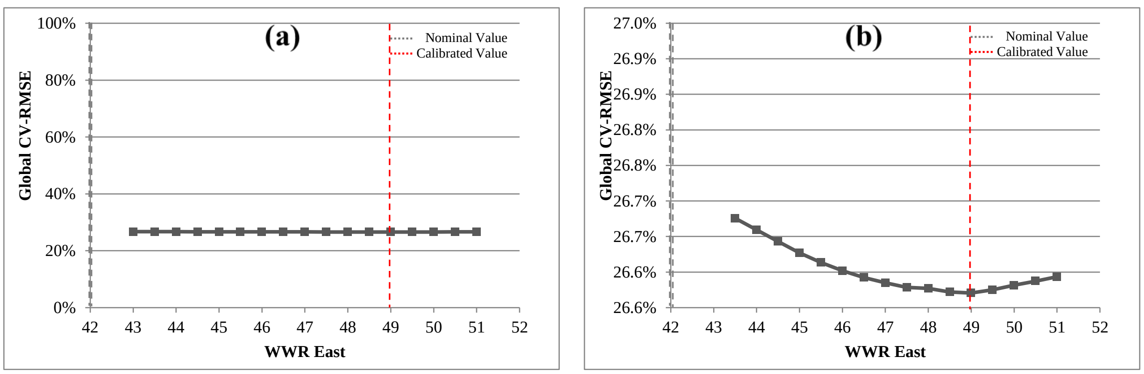


Figure G.43 Global CV (RMSE) Changes for WWR for East (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

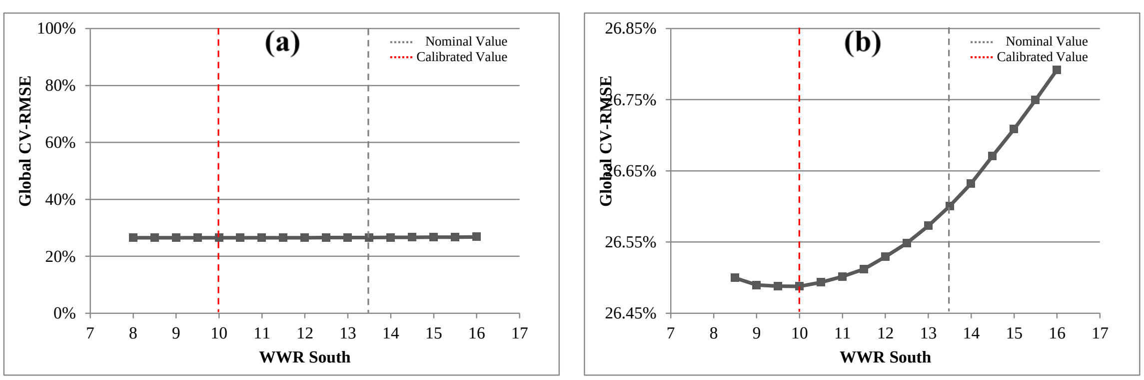


Figure G.44 Global CV (RMSE) Changes for WWR for South (2nd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

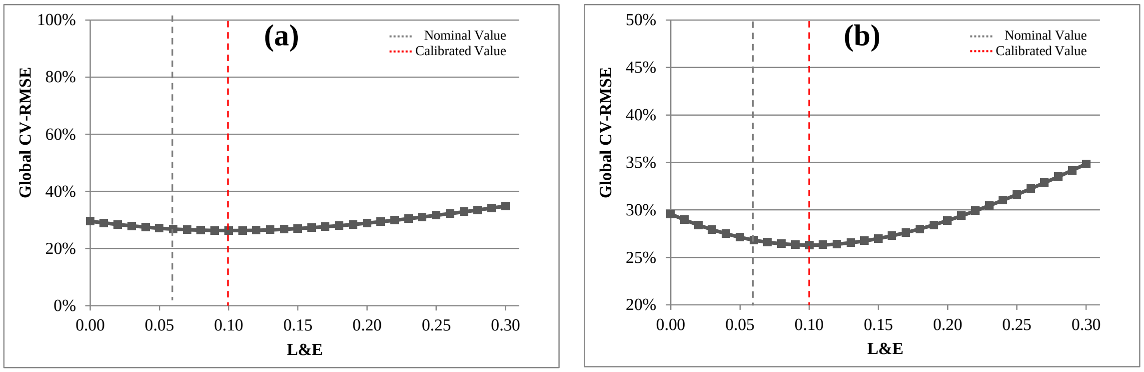


Figure G.45 Global CV (RMSE) Changes for L&E (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

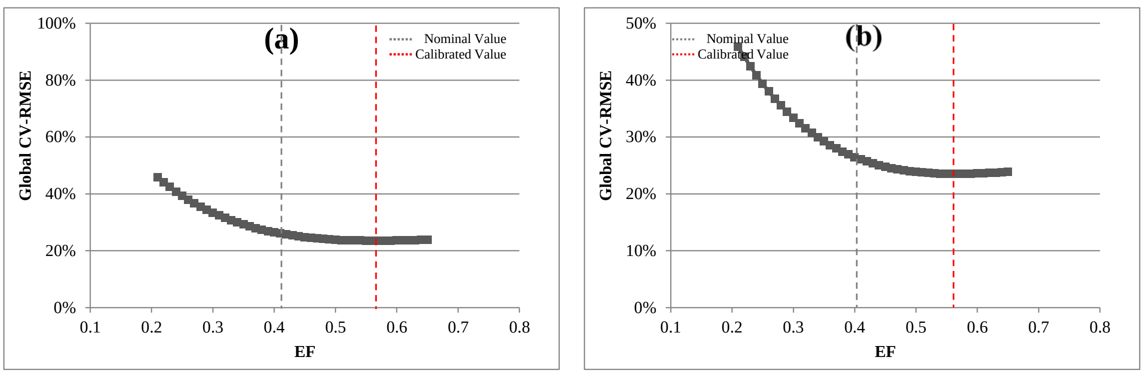


Figure G.46 Global CV (RMSE) Changes for EF (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

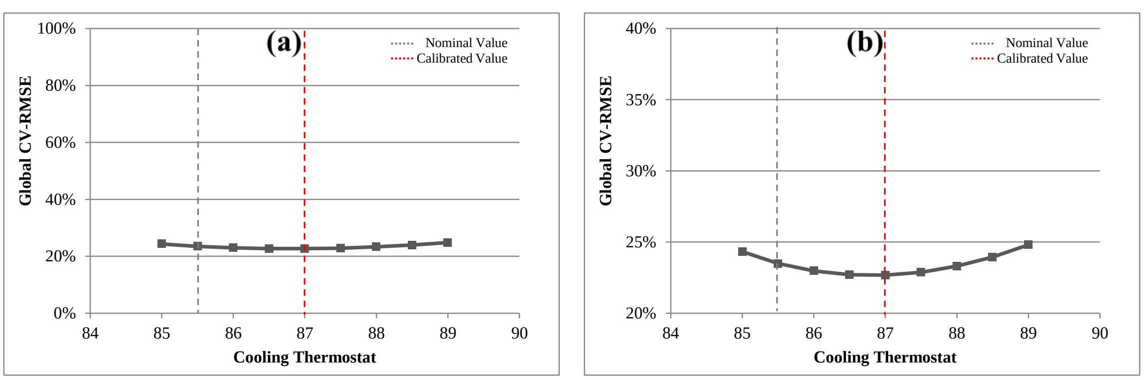


Figure G.47 Global CV (RMSE) Changes for Cooling Thermostat Setpoint Temperature (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

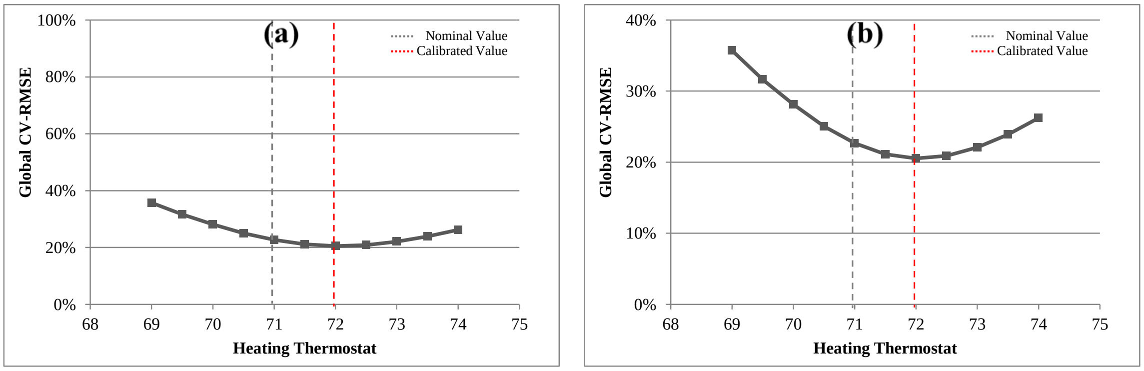


Figure G.48 Global CV (RMSE) Changes for Heating Thermostat Setpoint Temperature (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

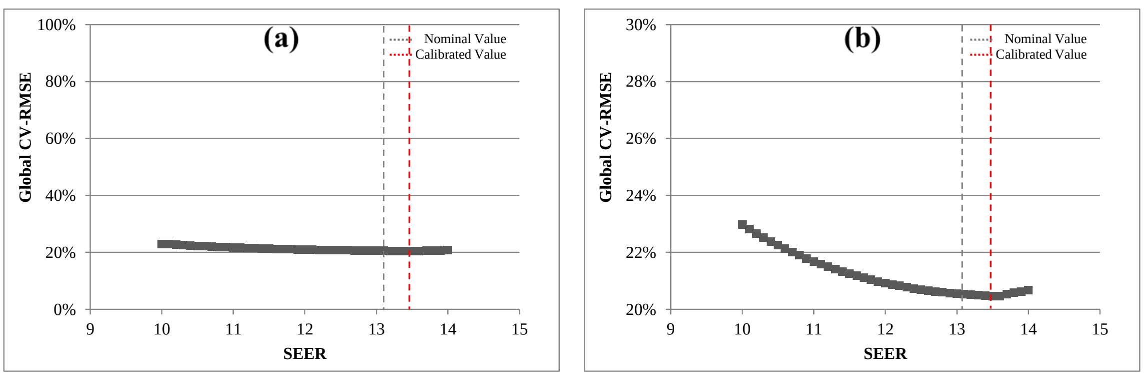


Figure G.49 Global CV (RMSE) Changes for SEER (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

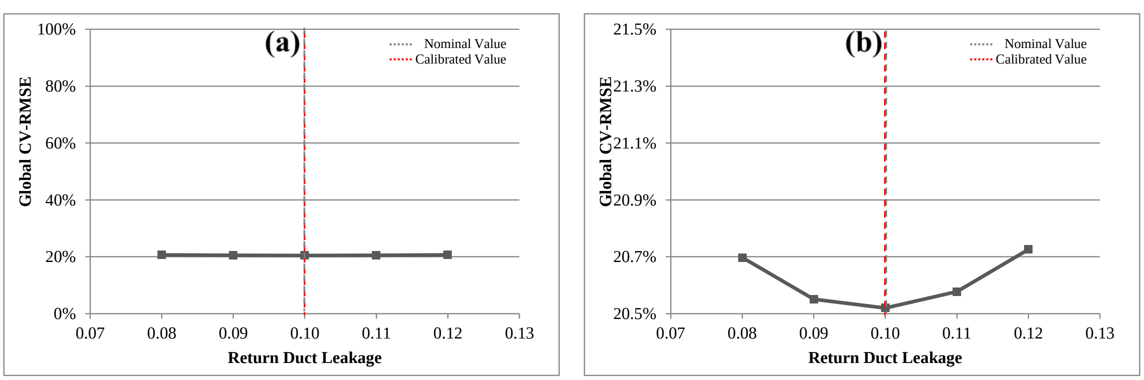


Figure G.50 Global CV (RMSE) Changes for Return Duct Leakage (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

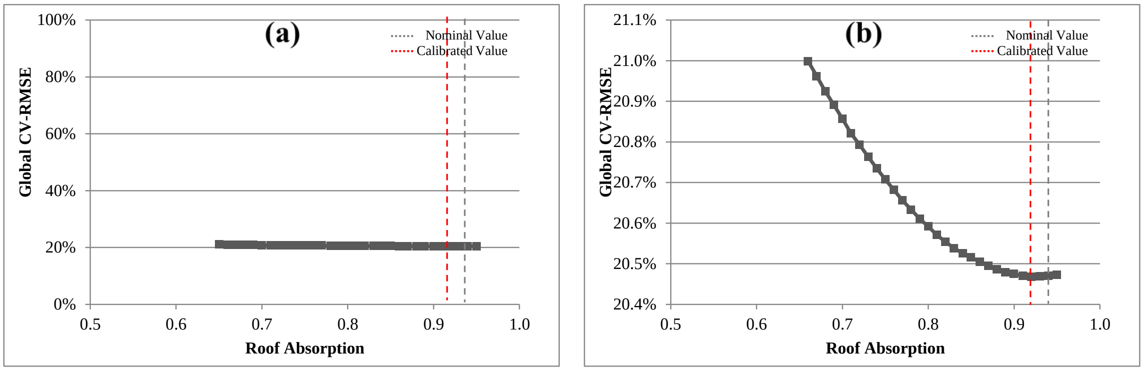


Figure G.51 Global CV (RMSE) Changes for Roof Absorption (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

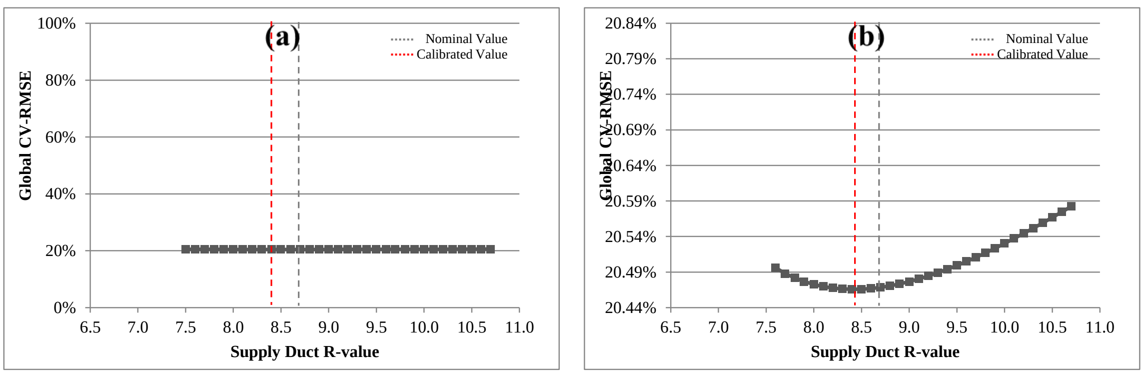


Figure G.52 Global CV (RMSE) Changes for Supply Duct R-value (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

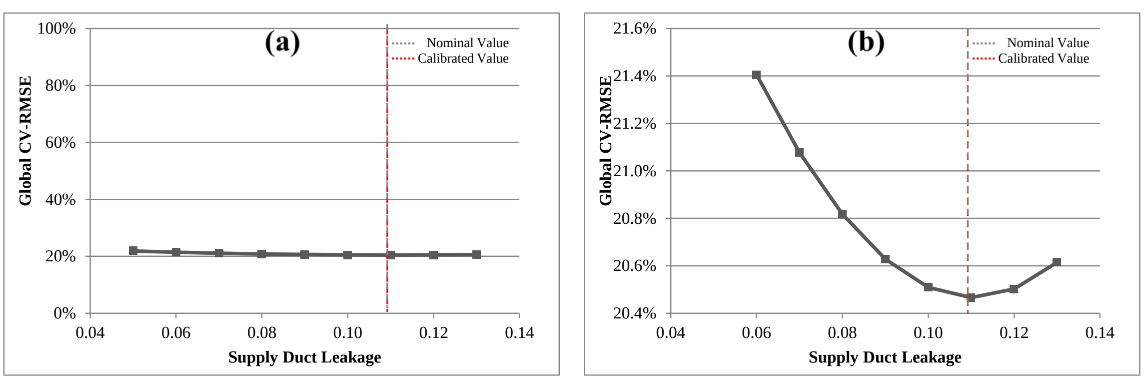


Figure G.53 Global CV (RMSE) Changes for Supply Duct Leakage (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

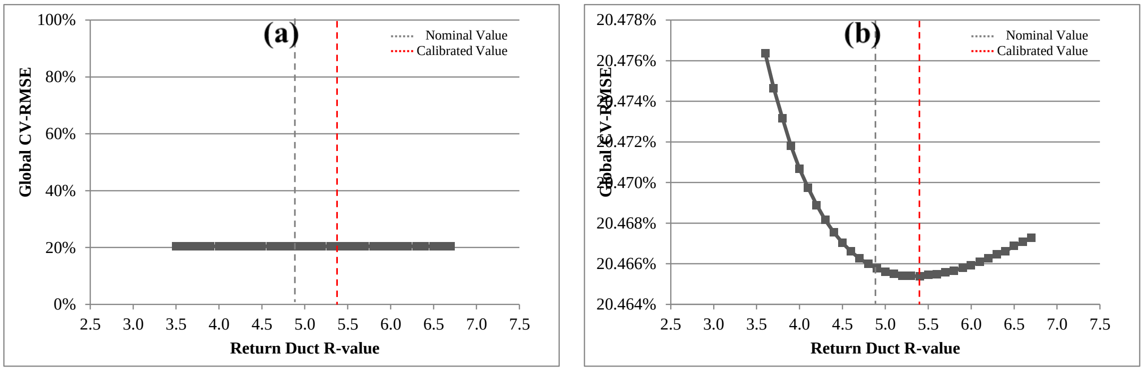


Figure G.54 Global CV (RMSE) Changes for Return Duct R-value (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

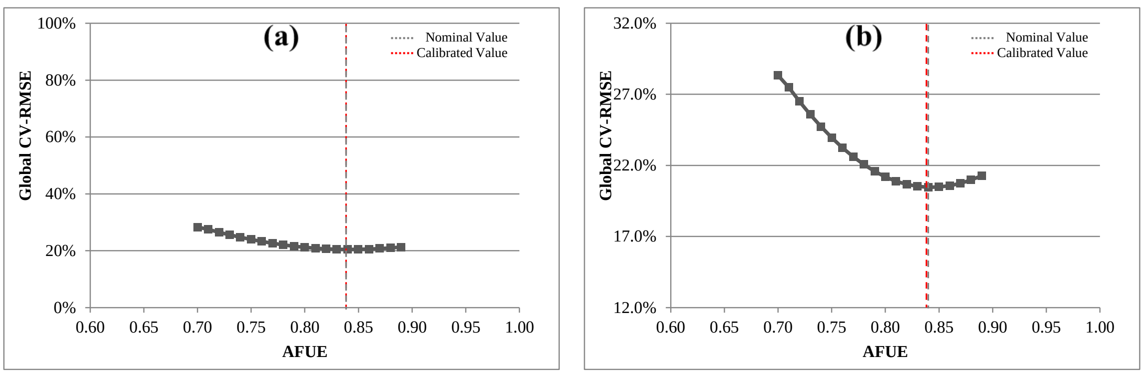


Figure G.55 Global CV (RMSE) Changes for AFUE (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

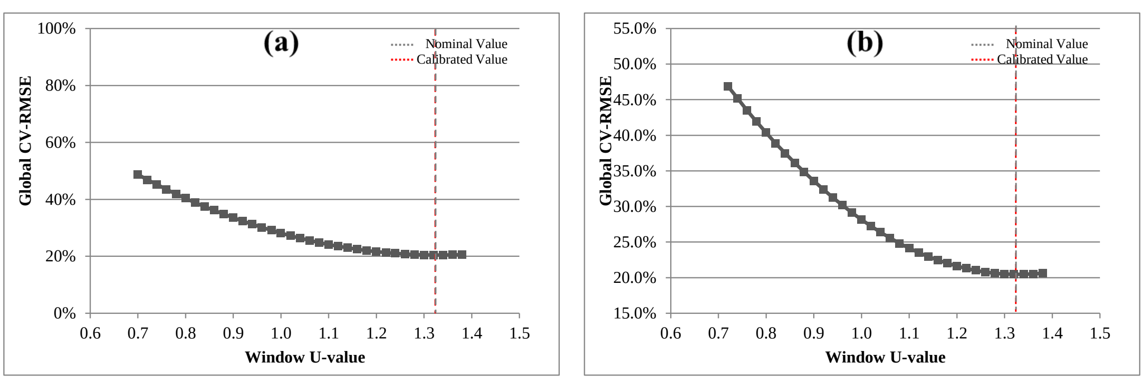


Figure G.56 Global CV (RMSE) Changes for Window U-value (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

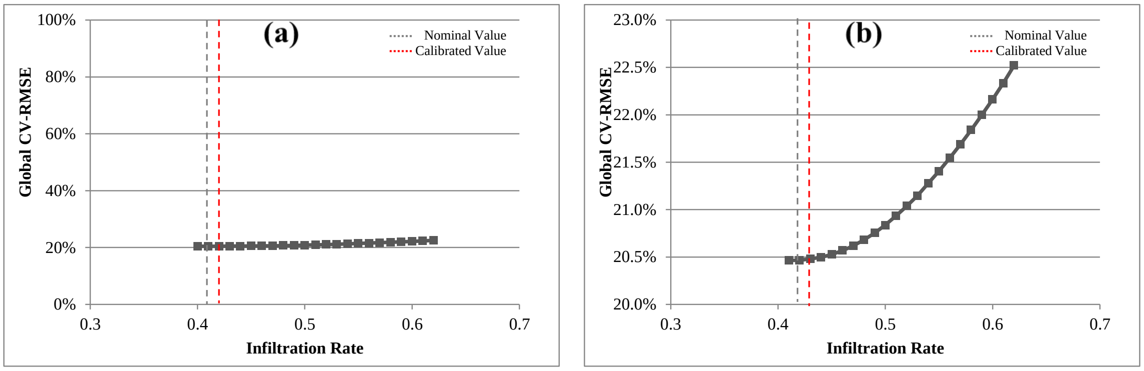


Figure G.57 Global CV (RMSE) Changes for Infiltration Rate (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

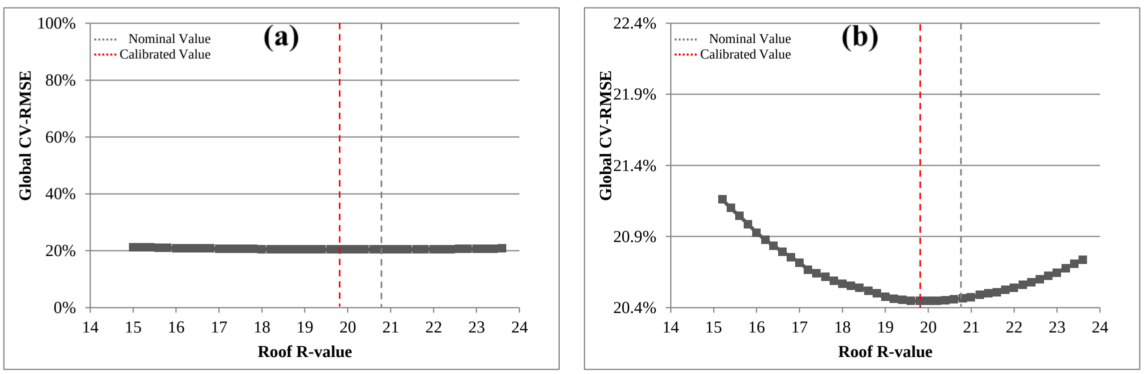


Figure G.58 Global CV (RMSE) Changes for Roof R-value (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

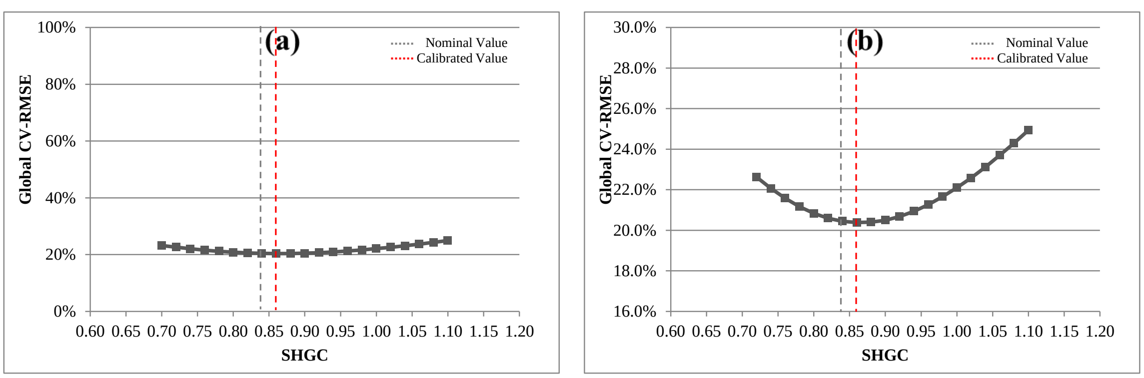


Figure G.59 Global CV (RMSE) Changes for SHGC (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

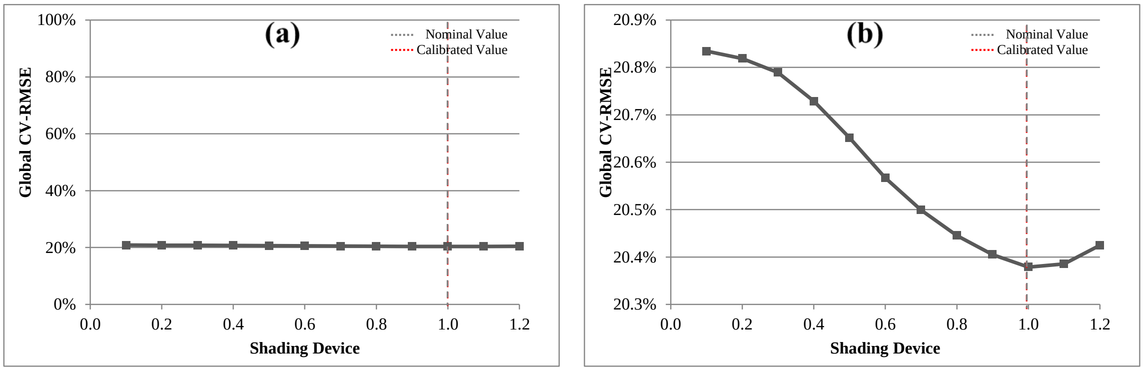


Figure G.60 *Global CV (RMSE) Changes for Shading Device (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

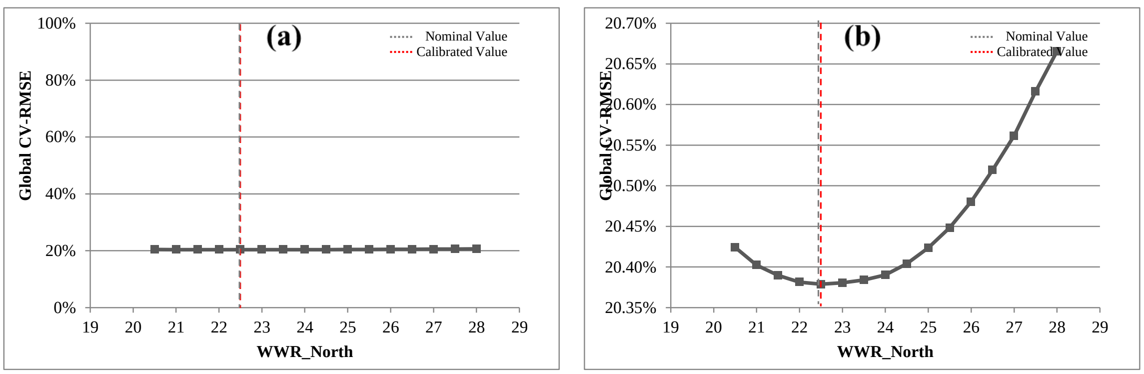


Figure G.61 *Global CV (RMSE) Changes for WWR for North (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

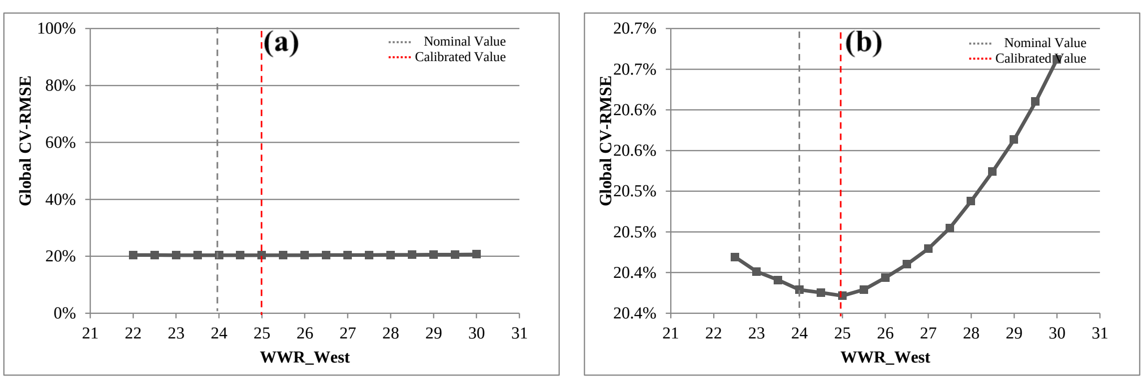


Figure G.62 *Global CV (RMSE) Changes for WWR for West (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

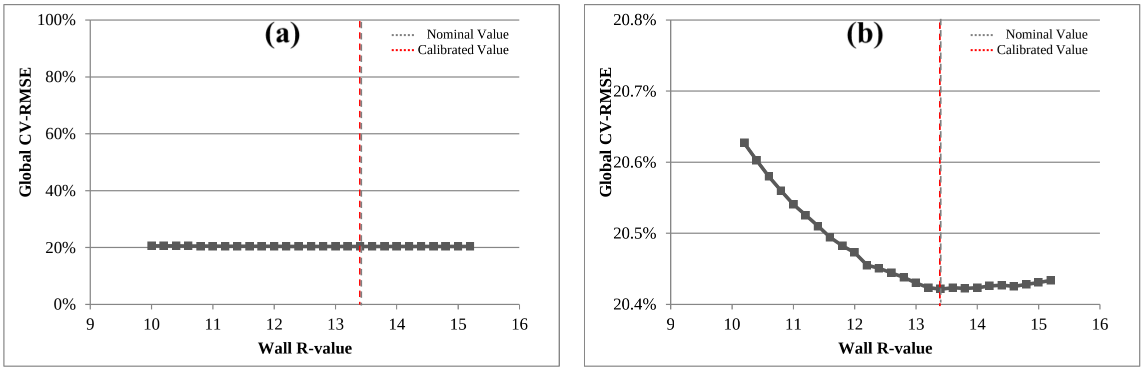


Figure G.63 Global CV (RMSE) Changes for Wall R-value (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

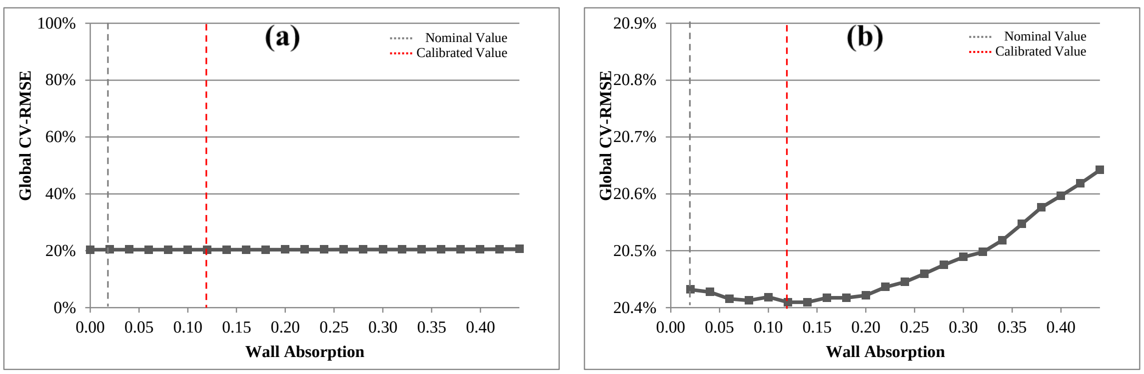


Figure G.64 Global CV (RMSE) Changes for Wall Absorption (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

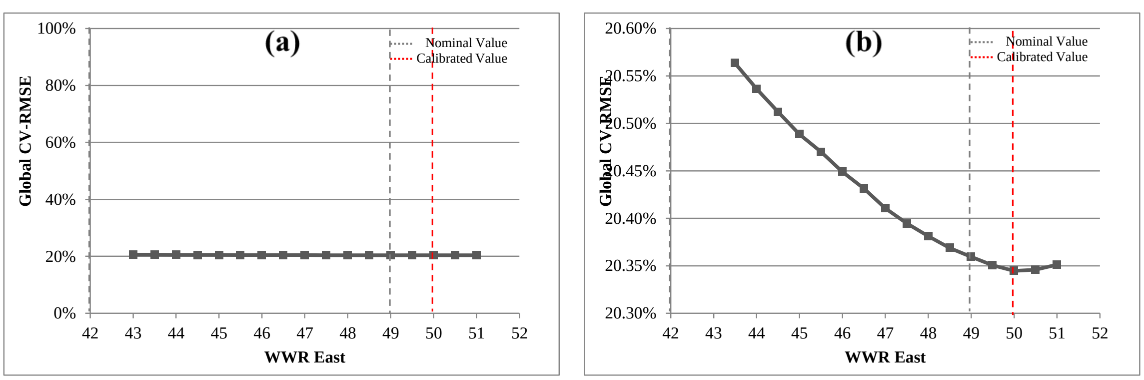


Figure G.65 Global CV (RMSE) Changes for WWR for East (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

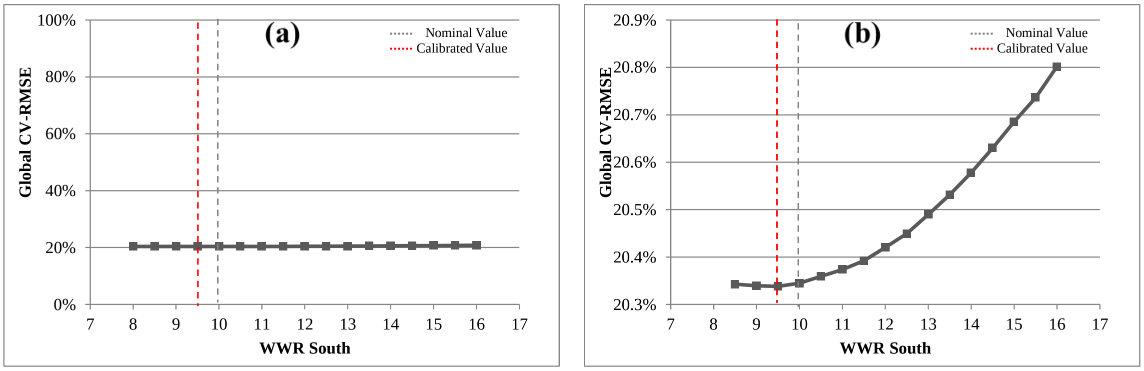


Figure G.66 *Global CV (RMSE) Changes for WWR for South (3rd Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

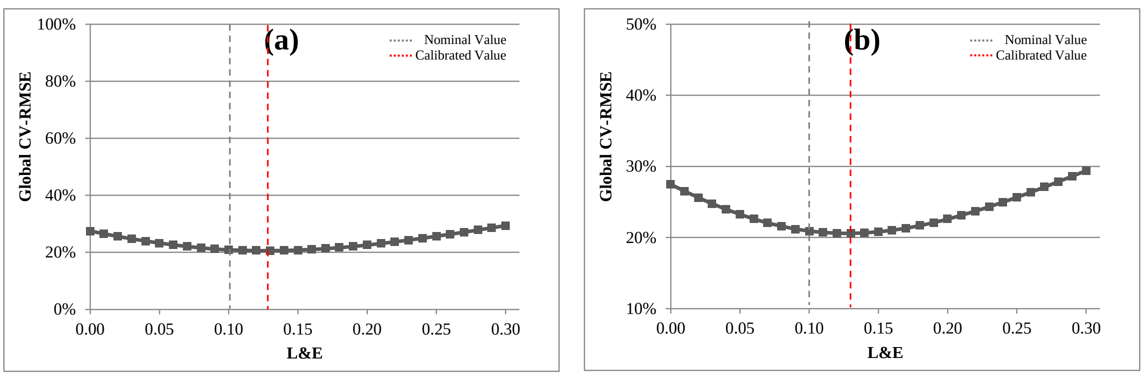


Figure G.67 *Global CV (RMSE) Changes for L&E (4th Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

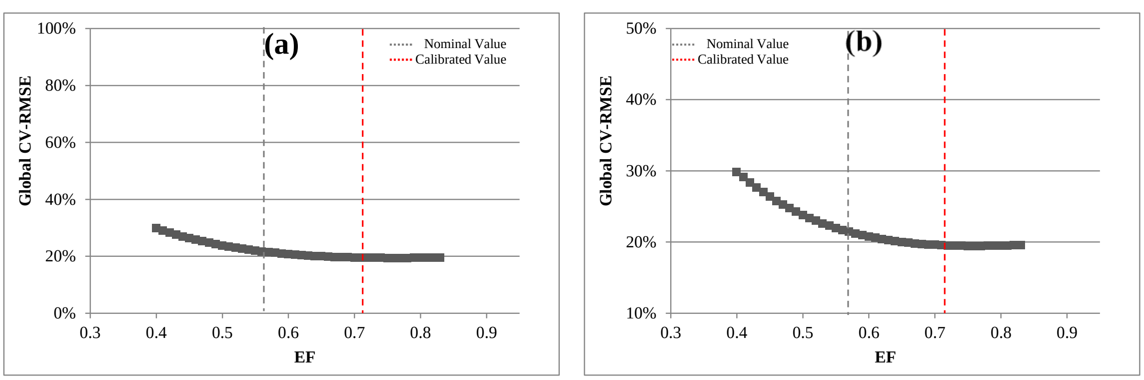


Figure G.68 *Global CV (RMSE) Changes for EF (4th Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis*

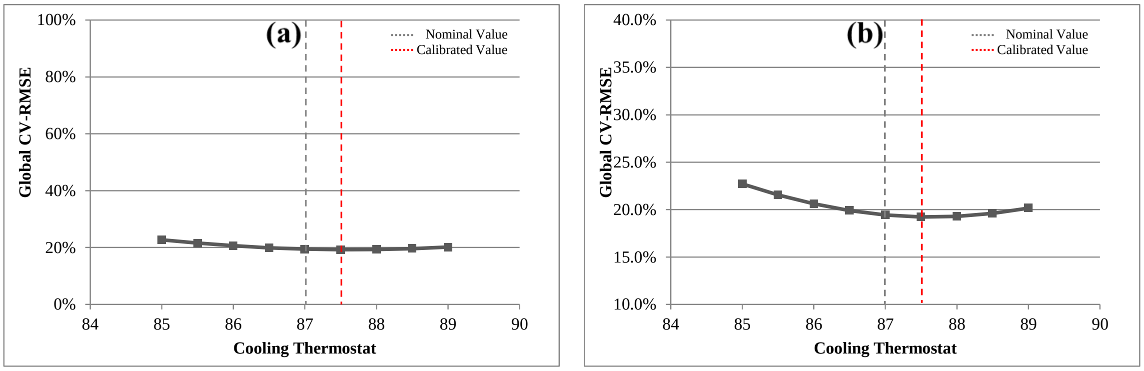


Figure G.69 Global CV (RMSE) Changes for Cooling Thermostat Setpoint Temperature (4th Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis

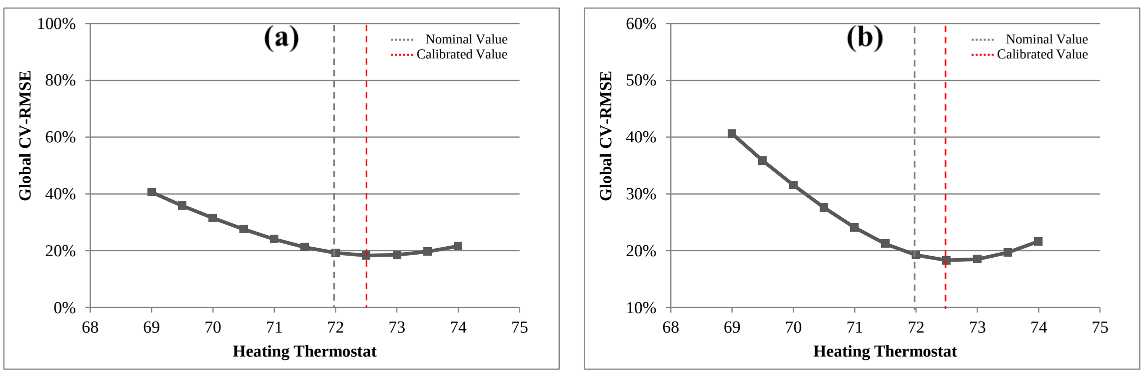


Figure G.70 Global CV (RMSE) Changes for Heating Thermostat Setpoint Temperature (4th Path): (a) 0% to 100% Scale in Y axis and (b) Adjusted Scale in Y axis